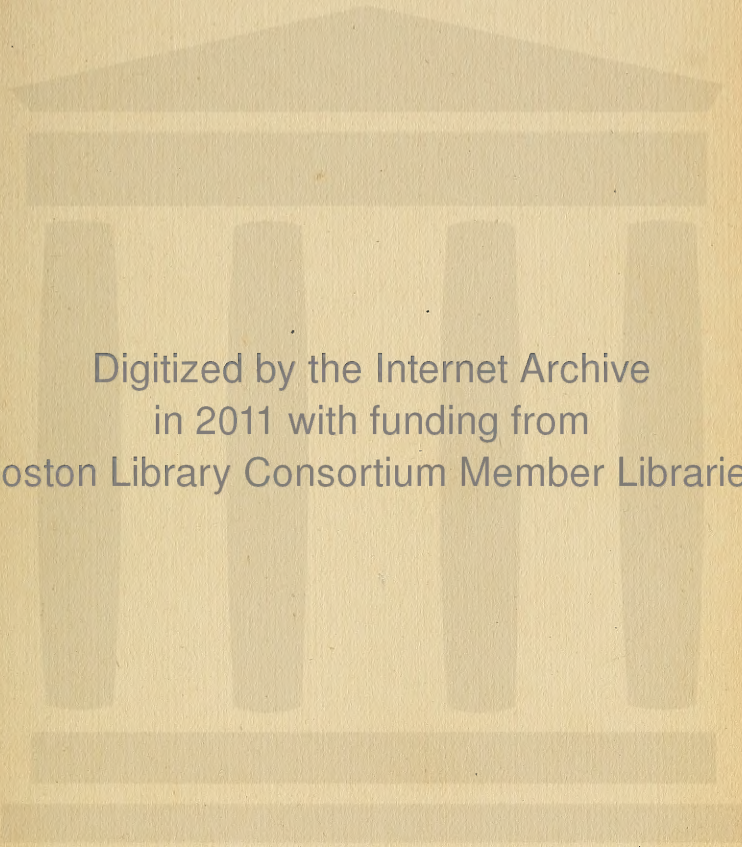


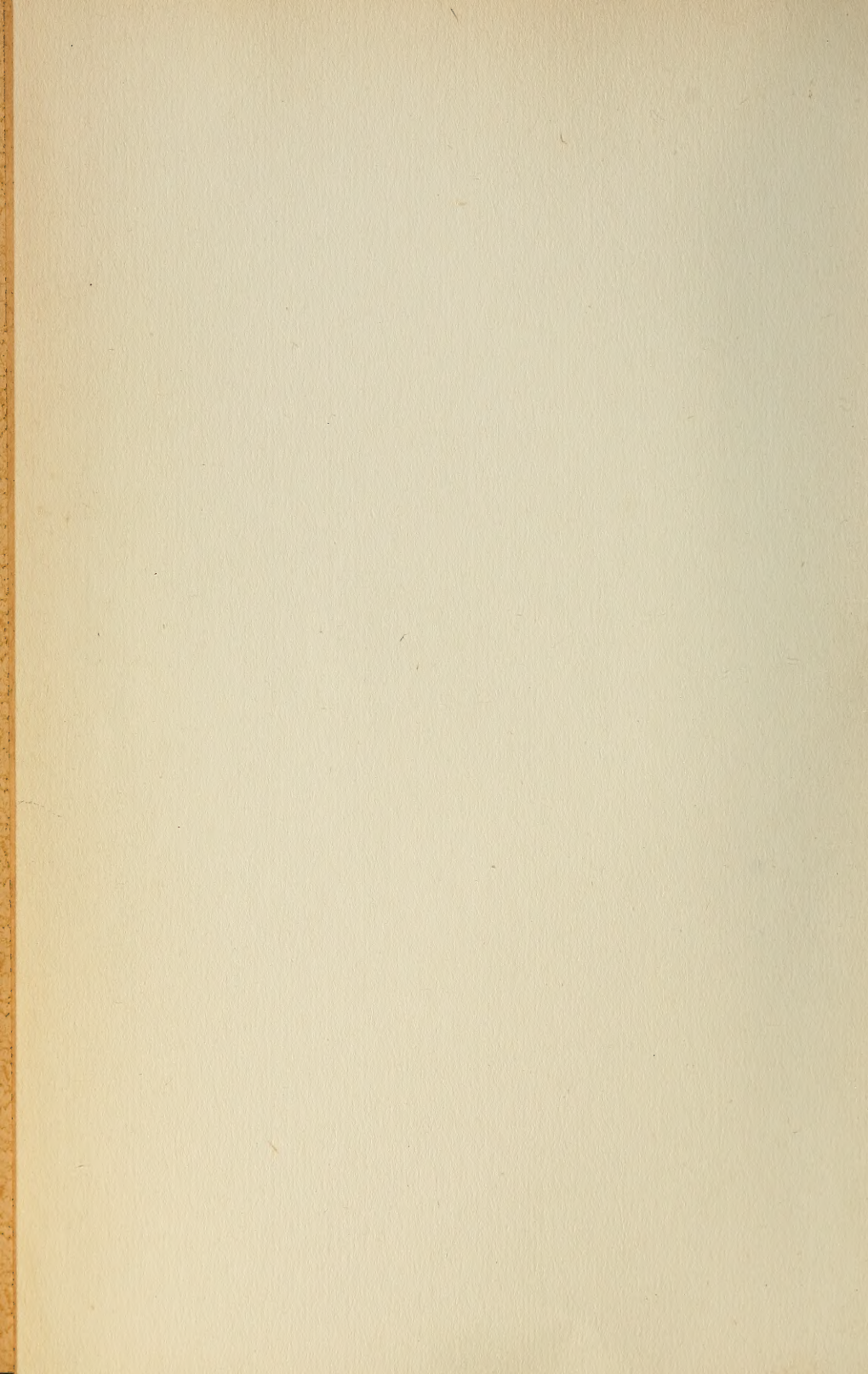


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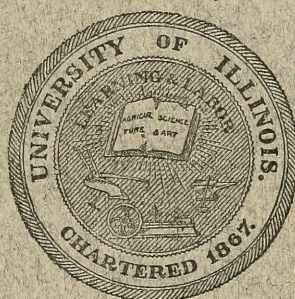
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BULLETIN NO. 31

FUEL TESTS WITH HOUSE-HEATING BOILERS

BY

J. M. SNODGRASS



UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 31

FEBRUARY 1909

FUEL TESTS WITH HOUSE-HEATING BOILERS

BY J. M. SNODGRASS, ASSISTANT PROFESSOR OF MECHANICAL
ENGINEERING, ENGINEERING EXPERIMENT STATION

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GENERAL INTRODUCTION

This bulletin describes one hundred thirty fuel tests with house-heating boilers. For convenience, it has been divided into three parts.

Part I describes 48 tests made by the Engineering Experiment Station of the University of Illinois, when burning the various kinds of fuel commonly used in house-heating work in the state of Illinois.

Part II relates to 58 tests made under the direction of the United States Geological Survey at St. Louis, Missouri. Of these tests, 47 were upon briquetted fuel, and 11 upon raw coal.

Part III describes 24 tests made by the Engineering Experiment Station of the University of Illinois, using briquetted fuel.

All these tests were conducted under conditions which differed considerably, and by methods differing more or less in detail. The tests made by the Engineering Experiment Station at the University of Illinois extend over a considerable length of time and have been carried on by regular members of the fuel test division, occasional changes in the personnel having been required. The observations on the tests made at St. Louis were all made by one observer. For these reasons, therefore, the results are hardly comparable, except in a more or less general way, and little attempt has been made to make such comparisons.

The descriptive matter and discussion included in each part apply to its own series of tests, unless otherwise stated. Most of this descriptive matter and discussion has been incorporated in connection with the tests of Part I. Part II and Part III are for the most part a compilation of data and results of the tests considered. The tests made at St. Louis under the supervision of the United States Geological Survey are reported and discussed in Bulletin 366 issued by that department. The Engineering Experiment Station is under obligation to the United States Geological Survey for the information concerning the St. Louis tests here published.

I. FUEL TESTS WITH HOUSE-HEATING BOILERS MADE BY THE ENGINEERING EXPERIMENT STATION (48 tests with representative fuels)

1. *Introduction*

The purpose of these tests was in general two-fold. First, to obtain the information usually obtained from boiler trials when operating upon house-heating boilers with various types of fuel commonly used for domestic purposes, in order that comparison might readily be made; second, to obtain information that might assist in developing satisfactory methods for conducting house-heating boiler trials whether the object of the test be to test the fuel, the equipment, or the two combined.

Some of the more important deductions drawn have been summarized in the paragraphs immediately following. The data and discussion relative to these deductions will be found in subsequent portions of the bulletin. The conclusions regarding methods for conducting house-heating boiler trials, having been drawn from one series of tests during which most of the important conditions were maintained constant, they can be considered as of only a preliminary nature. Further tests, under varying conditions, will, it is hoped, furnish further information in this connection. It was deemed advisable to present the information relative to the tests as fuel tests at this time together with such suggestions as could be made in regard to methods for conducting such tests.

2. *Summary of Conclusions*

A. *Efficiency and Fuel Cost*

(1). *The evaporative efficiencies* of house-heating boilers vary greatly with changes in other conditions and extreme care should be used in making comparisons.

(2). *The efficiencies* for the tests under consideration varied from 44% to 66%; thus covering about the same range or a somewhat lower range than is found in power boiler work.

(3). *A still wider range* of efficiencies will exist under the variable capacity conditions common to average residence heating work.

(4). *The range in efficiencies* found was due principally to the different kinds of fuel tested.

(5). *Fuels high in fixed carbon content*, such as anthracite and coke, give relatively high efficiencies as compared with fuels low in fixed carbon content.

(6). *Present methods of burning and present types of boilers* are particularly well adapted to burning anthracite and other coals high in carbon content.

(7). *Coke burning* presents special problems as to methods of burning and construction of equipment.

(8). *A high fixed carbon content* as opposed to a high volatile content is desirable in a fuel for domestic purposes.

(9). *The low efficiencies* with fuel of high volatile content, such as the Illinois coal, indicate the necessity of improvement as to equipment and methods of burning in order that this fuel may be placed more nearly on an equal footing with other fuels in this respect when employed for house-heating purposes.

(10). *Variations in efficiencies*, apparently due to slight changes in fire and other conditions indicate the possibility of obtaining higher efficiencies in many cases by careful attention to details relating to fuel, operation and equipment.

(11). *Illinois coal* may be obtained at from $\frac{1}{4}$ to $\frac{1}{2}$ of the cost per ton of anthracite. The cost per British thermal unit will be relatively slightly higher for Illinois coal than when expressed as cost per ton. Roughly, however, 10,000 B. t. u. can be purchased in Illinois coal at from $\frac{1}{4}$ to $\frac{1}{2}$ of the cost in anthracite.

(12). *Illinois coal* is considerably cheaper, expressed both as cost per ton and as cost per British thermal unit than Pocahontas coal or coke.

(13). *Fixed carbon* can be bought much more cheaply in the form of coke than as anthracite, and at as low or lower a price than it can be purchased in Pocahontas or Illinois coal.

(14). *With Illinois coal* as fuel, water can be evaporated in house-heating boilers at about 50% of the fuel cost of anthracite and about 75% of the fuel cost of Pocahontas coal or coke.

(15). *The relatively low cost* of Illinois coal especially as compared with the eastern coals will insure its continued use for domestic purposes. The amount of this fuel used for such purposes will probably increase in spite of the disadvantages at present

connected with its burning. This condition emphasizes the necessity for improvement in the methods of burning the cheaper fuel.

(16). *The low fuel cost of evaporation* for Illinois coal as compared with coke is considerable and will insure the continued use of the raw coal until prices of the two fuels are more nearly equal. Improvement in methods of burning and equipment are needed for burning each of these fuels and such improvements will, doubtless, affect the relative quantity of each which is used.

(17). *Improvements* tending toward a reduction of smoke, dirt or other disadvantages connected with the burning of the cheaper coal will, doubtless, also increase the efficiency with which that fuel may be used and make the fuel cost differences still more favorable to the cheaper fuel.

(18). *Based upon present prices* of Illinois coal and considering evaporative performance only, anthracite, for instance, is worth only from \$3.00 to \$4.00 per ton. The additional amount which is paid for it must be considered as expended for advantages possessed by the anthracite, such as cleanliness and ease of fire control, which are not possessed by the other fuel.

B. Cleanliness, Control, Attendance

(19). *Anthracite and Pocahontas* coal are particularly well adapted to maintaining uniform pressure and fire conditions over a long period of time with little attention. The quick-burning Illinois coals are much less reliable in this respect.

(20). *Satisfactory regulation* is more readily accomplished with the eastern fuels and with coke than with the Illinois coal.

(21). *The total attendance* required may be considerably less when burning anthracite than the other fuels. The same may be said in general as between coke and Pocahontas as compared with the Illinois coal. This condition would be especially noticeable in connection with heating apparatus used in residence work.

(22). *Anthracite and coke* possess marked advantages over the other fuels, especially over the Illinois coal, with respect to cleanliness. They are in general cleaner in and about the boiler room and do not smoke, either from the chimney or in the boiler room. Little trouble is had with soot or ash in the flues and with reasonable care noxious gases should not be given off in the furnace room; also, the ash is small in amount and easily handled.

Clinkering may take place to some extent.

(23). *Pocahontas coal* is less clean to handle than anthracite or coke, makes some smoke, soot and other dirt and burns with a small amount of very easily handled ash which is not apt to clinker.

(24). *Illinois coal*, comparatively speaking, smokes badly, deposits a large amount of soot in the flues, may cause the emission of smoke and noxious gases into the boiler room. It is dirty to handle in and about the boiler room. The amount and performance of the ash in the fire-box vary considerably with different kinds of Illinois coal. In general, however, the ash is considerable in amount and clinkers to a greater or less extent, sometimes badly.

(25). *Washing and sizing Illinois coal* eliminate to a very considerable extent the objectionable features with regard to smoke, soot, dirt and ash just mentioned.

C. General

(26). *In considering house-heating boiler tests*, a number of important considerations, such as efficiency, fuel cost, attendance, control, cleanliness and equipment must be taken into account. The relative importance of such factors can not be stated definitely and varies greatly with the nature of the service required of any given installation.

(27). *Efficiency and fuel cost* may become the items of greatest importance where heating work is upon a comparatively large scale approaching power boiler conditions.

(28). *Simplicity and the ease* with which the heating apparatus can be cared for may be of greater importance than high evaporative efficiency.

(29). *The condition which requires the minimum amount of attendance* may be the most satisfactory and economical and more than offset the consumption of some extra fuel.

(30). *The ability to get up steam quickly*, and to maintain uniform pressure and fire conditions over comparatively long periods of time may be of greater importance than questions relating to either fuel or equipment.

(31). *The desire or necessity for cleanliness* with respect to smoke, soot, ash and dust or dirt in the boiler room, may warrant the use of high priced fuel.

D. Method of Conducting Tests

(32). *In general* the test should be made under conditions approximating those of the service which is required of the fuel and equipment. To do this will require tests of two kinds.

(a) *If the load demand is fairly constant and comparatively high*, test at the required load in a manner generally similar to that employed in power boiler work, making evaporative performance the main item sought.

(b) *If the load demand is very variable*, test under conditions approximately similar to operating conditions. In such tests questions relating to attendance, cleanliness and control will generally be found of equal or greater importance than those relating to efficiency and the tests should be so conducted as to give the fullest information possible along these lines.

(33). *Make the tests* classified under (a) of paragraph 32 at least 16 hours long and to consist of at least three firing charges of fuel.

(34). *Make the tests* classified under (b) paragraph 32, 24 hours long.

(35). *Use the standard method* for starting and stopping all tests, that is, start the test with a fresh fire and close it by drawing the fire and allowing for the residue of unconsumed fuel thus obtained.

(36). *No conclusions are offered* as to the best method of conducting tests for the purpose of determining the proper rating to be given to particular apparatus. Further tests to be reported upon later will, it is hoped, be of service in this connection.

3. *General Discussion of the Problem Relating to Tests of Fuel in House-heating Boilers*

(1). To determine the relative value of a fuel for different purposes or of different fuels for a given purpose, it generally seems advisable to make the tests in connection with the apparatus with which the fuels would ordinarily be employed, and under conditions at least approximately similar to those of every day practice. Laboratory methods, such as chemical analysis and calorific determination, are in general considered as only a part of a fuel test and are employed along with other data in interpreting the results. We thus have fuel tests made in connection

with boilers, gas producers, coking ovens, furnaces, and other devices in order that the results and deductions may be applicable to the particular problem in hand. In any given branch of fuel testing this process of applying particular conditions may be carried still further.

(2). *Small heating units as compared with large units.*—The fuel tests here considered were made in connection with house-heating boilers of comparatively small size. On account of the small amount of available information relative to a satisfactory method for conducting house-heating boiler tests, one of the principal purposes in conducting these tests was to obtain information that would assist in developing such a method. Fuel tests with house-heating boilers will of necessity be similar, in many respects, to the tests made in connection with power boilers. While not overlooking the difference which must exist, due to the unlike conditions under which these two types of boilers operate, and the purposes for which each type is operated, it was deemed advisable as a first step in this work to make a series of tests upon house-heating boilers as nearly as possible by the methods which have been found satisfactory when testing with power boilers.

In work with the large units, fuel cost is generally the important factor, and the highest evaporative performance that can be obtained per dollar expended for fuel is the condition desired. Conditions relating to attendance, equipment, cleanliness and methods of operation are of secondary importance, and are capable of considerable variation or adjustment (depending upon the size and importance of the installation) in order to obtain a high rate of evaporation. Conditions surrounding house-heating boilers are, however, of such a nature that they can not be readily changed. Higher rates of evaporation and more efficient rates of combustion could, doubtless, often be obtained by having a fireman in constant attendance. The cost of such attendance is, however, in most cases prohibitive. The use of unusually expensive, complicated, or large apparatus is from the nature of the service undesirable. Conditions relating to equipment and attendance may be of so much greater relative importance than low cost of evaporation as to permit of relatively inefficient performance in order to satisfy those considerations. In many instances it will be found that the condition which requires the minimum amount of attendance is the condition which is most satis-

factory and the advantage of simple, easily cared for equipment will more than offset the consumption of some extra fuel. It may be of much greater importance to get steam up quickly, or otherwise produce the desired heating effect quickly, and to be able to maintain a uniform rate of heat generation through a considerable length of time, than it is to furnish that heat at the lowest possible fuel cost. Such considerations may warrant the use of high-priced fuels or the sacrifice of evaporative efficiency for the sake of ease of fire control. Regulation, ease with which good fire conditions are maintained with respect to ash and clinker, the tendency of flues to become fouled, dirt in the form of dust, smoke, soot, or ash, whether from the coal pile, the fire-box, or chimney, are all important considerations aside from their relation to evaporative performance.

(3). *Outline*.—In order that the results of house-heating boiler tests may be of the greatest use, it becomes desirable to report more or less fully upon quite a number of conditions. The following outline presents most of the questions which will arise in making fuel tests with house-heating boilers.

Efficiency

- (a) Evaporative performance, including efficiencies of the boiler and furnace, grate, and of the plant.
- (b) Fuel cost for heat delivered.

Control

- (a) Time required to get up steam pressure.
- (b) Length of time of holding uniform pressure and satisfactory fire conditions without attention.
- (c) Uniformity of regulation.
- (d) Total attendance.
- (e) Capacity.

Cleanliness

- (a) Dust and dirt in boiler room.
- (b) Ash and clinkers.
- (c) Soot and ash in flue.
- (d) Smoke.
- (e) Smoke and gases in furnace room.

(4). *Relative importance of conditions*.—It is obviously impossible to measure exactly just what is the relative importance of the factors as above grouped under control and cleanliness, as

compared with boiler efficiency and evaporative performance, but it is evident that they are of much greater relative importance when considering house-heating boilers than when considering power boilers. It is also true that the importance of certain factors will vary greatly according to the service rendered. In heating large school buildings with house-heating boilers the conditions may approximate very closely conditions in power work, and evaporative performance will be the item of greatest importance, while in the case of heating a small residence, cleanliness and ease of control may readily seem to be of first importance.

(5). *Capacity*.—The problem or problems in connection with each of the items mentioned are probably evident, with the possible exception of the item *capacity* which is listed under the head of control. In the case of a house-heating boiler, the question relative to capacity which is of importance, is how many square feet of radiation can be served by the boiler through comparatively long periods of time without attention, except at the time of firing. It is generally desired to know how many square feet of radiation can be served through a period of from six to eight hours without attention during that time. The same amount of fuel consumed within a short time should serve more radiating surface per hour than when burned during a longer period of time. The one hour period as employed in defining a horse-power, and as used in rating power boilers, is not satisfactory for comparative purposes in connection with house-heating boiler work. In this kind of work, then, in order that information relative to capacity may have the greatest usefulness, it should be based upon the evaporation which can be obtained during a period of from six to eight hours without attention, rather than upon the evaporation obtained in one hour with whatever attendance may be required. Thus a boiler rated at 1000 square feet should be capable of serving that amount of radiation without attention for a much longer time than one hour. In order to give satisfaction as a house-heating boiler, it should probably be able to serve that radiation for a period of at least six hours without attention during that time.

(6). *Purpose of tests*.—In carrying on the tests herein reported it soon became evident that it would be difficult to conduct tests so that suitable data concerning all of the above mentioned items could be obtained from any one test. Tests so run that the data would be of the greatest comparative value, for instance, in the

case of the items grouped under efficiency, made the data concerning some of the items appearing under control and cleanliness, of little value in their relation to house-heating conditions. The lack of a satisfactory method of making tests, or of one generally accepted as such, was apparent. Under these circumstances it was deemed advisable to make a series of tests according to the A. S. M. E. code for conducting boiler trials. Accordingly, the tests herein reported have been, in the main, run in accordance with the recommendations contained in that code. The purpose of the tests thus becomes twofold; first, to obtain the information usually obtained from boiler trials when operating upon house-heating boilers, with various types of fuels; second, to obtain information that might assist in developing satisfactory methods for conducting house-heating boiler trials. The second end, it was thought, could best be attained by at first making use of the A. S. M. E. code. The adoption of this code as a guide in conducting the tests tends to lay the greatest stress upon questions relating to evaporation and efficiency. While not overlooking the importance of questions relating to capacity, regulation, attendance, and cleanliness, conditions were so arranged as to make evaporative performance the main item sought, and the best basis of comparison for this particular series of tests. It is, however, intended to conduct several additional series of tests in which more attention may be given to some of the other items just mentioned.

(7). *Variable conditions.*—Fuel or steaming tests in connection with boilers as small as the average house-heating boiler, and especially when carried on under the average conditions under which such boilers are operated, present difficulties which are much more pronounced than when conducting similar trials upon larger apparatus. The low rate of combustion under ordinary circumstances, and the low capacity at which the average house-heating boiler is operated, either all or part of the time, tend to make the results of different tests unsatisfactory for purposes of comparison, as it is exceedingly difficult under these circumstances to obtain uniformity of conditions between different tests. Apparently slight variations in fire conditions might have considerable influence upon results.

(8). *Amount of fuel consumed.*—The determination, with sufficient exactness, of the amount of fuel consumed presents difficulties in the case of small apparatus which are not encountered to the same extent with larger apparatus. The quantities of coal burned and water evaporated for tests of equal length may easily be ten or twenty times as large when testing with a power boiler as when testing with a house-heating boiler, and errors in determining these quantities may readily be a much greater percentage of the total in the case of the small boilers. Errors of this kind are in general most likely to occur at the beginning or end of the test, as in judging the amount of fuel consumed, or determining the weight of the water in the boiler. Probably the most noticeable error of this kind is to be found in the usual or so-called alternate method of starting and stopping boiler trials. The alternate method of the code of the American Society of Mechanical Engineers for conducting boiler trials provides for beginning and ending the test when the fire conditions are such that equal amounts of unconsumed combustible and of ash are upon the grate for the two times under consideration. That this condition may be met requires judgment and careful operation. In the average power boiler trial the fuel burned and ash removed amount to many times that which may be upon the grate at the start or stop of the test, and a mistake in judging the fire conditions at those times will make a comparatively small error in subsequent calculations. This, however, is recognized as a possible source of error of considerable importance, under the most favorable conditions, when testing power boilers. In the case of very small boilers, especially in those having a comparatively deep fire bed such as is often used in house-heating boilers, the quantity of fuel upon the grate at the beginning and end of a test would be a very considerable proportion of the total fuel burned, unless the test was of considerable length. About the same assumptions with regard to the two types of boilers would show that the error expressed in per cent of fuel consumed might readily be four or five times as great in the case of the house-heating boilers as in the case of the power boilers.

(9). *Standard method for starting and stopping test.*—This difficulty can be met in two ways. The test can be made longer, in which case the error becomes correspondingly smaller as expressed in per cent, or a method of starting and stopping the

test can be employed, intended to eliminate or diminish the error. The standard method of the code of the American Society of Mechanical Engineers provides for the raising of steam pressure by means of a preliminary fire, withdrawing that fire and beginning the test with a new fire built with a known weight of fresh wood and coal. At the end of the test, the fire remaining is drawn and allowed for in subsequent calculations. When testing power boilers the standard method occasions some additional work and trouble, and there is considerable difference of opinion even among experts as to which method, the alternate or the standard, is the better. By far the greater number of boiler trials are probably begun by the alternate method, on account of that being the more convenient, and because of this lack of definiteness as to which method is the better. In the case of the house-heating boiler the comparatively large amount of fuel upon the grate; the lack of uniformity of fire conditions at different times during the test; the difficulty of duplicating fire conditions as desired; and the difficulty of accurately estimating the amount of unconsumed fuel and ash in the fire-box, make the alternate method of starting and stopping unsatisfactory, and necessitate some plan more in accordance with the standard method, in order that the fuel consumed may be determined with sufficient accuracy.

(10). *Tests by societies and individuals.*—Societies and individuals interested in this kind of work have from time to time reported tests, or discussed methods for making such tests, but apparently without making definite recommendations that have been found satisfactory for the guidance of others, or that have been adopted generally enough to make comparisons possible or of value. The number of tests of this kind which have been reported is surprisingly small as compared with the number of tests conducted upon power boilers. Probably the greatest amount of work in this line has been done by the manufacturers of heating apparatus. The results of their investigations are, however, either not available or are applicable to particular makes of apparatus only, rather than to the problem as a whole.

4. *Fuel*

Table 1 presents in tabulated form the different kinds or types of fuels tested, the section of the country from which they were received, and their size.

TABLE 1
DESCRIPTION OF FUELS TESTED

Kind or Type of Fuel	Commercial Name	Size inches	Source of Fuel
Anthracite.....	Egg.....	2 $\frac{3}{4}$ to 2	Wyoming District, Pa.....
Pocahontas.....	Lump.....	*	Mercer County, W. Va.....
Coke—Gas-house by-product.....	Crushed.....	3 $\frac{1}{2}$ to $\frac{3}{4}$	Mnfd. by U. & C. Gas Co., from Youghiogheny coal.....
Coke—Solvay process.....	Crushed, Nut size.....	1 $\frac{3}{4}$ to $\frac{3}{4}$	Obtained from Chicago market.....
Illinois.....	Nut.....	1 $\frac{3}{4}$ to 1	Williamson County.....
Illinois.....	Screened lump.....	*	Macon County.....
Illinois.....	Screened lump.....	*	Vermilion County.....

* All large lumps were broken to pieces 6 inches or less in diameter.

The fuels here listed are fairly representative of those used in house-heating work in the state of Illinois, namely: anthracite coal, eastern bituminous coal, coke and Illinois coal. The Illinois coals are typical of those most commonly used in this section of the State, coming from the southern, eastern, and central portions of the State. These fuels were purchased in the local market, either Champaign or Urbana, in lots of three tons or less, with the exception of the Solvay coke, which was obtained from the Chicago market. The anthracite and the Illinois coal from Macon County were, judging from the appearance, rather below the average quality of coal of these kinds as they appear in this market. Chemical analyses, given in Table 12, page 74, Appendix A, give more exact information as to the exact composition of all of the fuels used. Taken as a whole, however, judging from general appearances, these fuels were fair samples of what the average householder might expect to obtain.

5. *Methods of Conducting Tests*

(1). *Starting and stopping the test and handling the fire.*—The methods recommended by the A. S. M. E. code for conducting boiler trials were in general followed in conducting these tests. The tests varied in length from 7.97 hours to 26.53 hours. With each fuel, tests approximately 8, 16, and 24 hours long were made upon each of the two boilers. The standard method of starting and stopping the trials as prescribed by the A. S. M. E. code was used. Steam pressure was raised by means of a preliminary fire, and the boiler run at a pressure of at least five pounds for a short time to insure fairly uniform conditions in and around the boiler. The preliminary heating usually required about one hour. At the start of the tests the preliminary fire was rapidly removed

and a fresh fire started with a weighed amount of wood and the first charge of coal. The test was started when the wood was ignited, at which time observations of time, water-levels, and pressures were taken. The kindling and entire amount of first charge of coal were ordinarily fired before the fire was lighted. The only exceptions to this were in cases where the kindling was ignited by the hot grates before all of the coal was fired. This, however, only delayed the firing of the entire charge of coal a few minutes after the start of the test. In all tests made with Boiler D₁, 75 lb. of fuel were fired at a time, and in all tests made with Boiler D₂, 105 lb. of fuel were fired at a time. These amounts, as compared with each other, are closely proportional to the grate surfaces of the two boilers. On account of all fuel charges being the same in amount, and also on account of the fact that a test was not ended until the fuel was so completely burned that pressure could no longer be maintained, many of the tests varied considerably from the 8, 16, or 24-hour period under which they are classed. A pressure of approximately five pounds was carried on the boiler. After a charge of fuel had been fired, the fire was not again touched until the next firing, if the automatic regulation was sufficient to keep up steam pressure without other attention. In case it became necessary in order to maintain pressure, there being plenty of unconsumed fuel in the furnace, the fire was poked or otherwise worked as seemed desirable.

(2). *Method of firing.*—For the tests with anthracite, coke and Pocahontas coal the fuel was fired by the spreading method, that is, the fresh fuel was spread about evenly over the entire grate surface. For the Illinois coals, on account of the liability of explosions due to gas collecting in the combustion chamber and flues, it was deemed advisable to fire by a method approaching the coking method. With the boiler D₁ the fresh fuel was fired more heavily at one side of the furnace than at the other, allowing the fire to burn up brightly much more quickly upon the side thinly fired than would otherwise have been the case. With boiler D₂ the burning fuel which remained in the furnace just before firing, was in part pushed or raked toward the rear of the grate, and the greater part of the fresh charge fired in front. This allowed the fire upon the back part of the grate to burn brightly almost from the time of firing.

(3). *Attention.*—The effort was made throughout to reduce to a minimum the amount of attention given the fire between times of firing. The attention which the fire did receive, however, which might be considered as additional to what would be expected in ordinary house-heating work, was given in accordance with the desire to have the tests fairly comparable upon an evaporative performance basis, rather than to obtain data relative to attendance conditions.

(4). *Ash and residual fuel.*—The fire was drawn at the end of the test, when the boiler pressure dropped below four or five pounds on the last firing, and did not again rise upon the opening of the damper and the closing of the check. Just as the grate was dumped, final observations concerning time, water, temperatures and pressures were taken. The material drawn out at the close of the test was immediately put into a galvanized can with a close fitting cover to prevent further combustion. Analysis of this partly consumed or residual fuel furnished suitable corrections in the determination of the amount of fuel actually burned. The ash was kept separate from the residual fuel, being taken from the furnace and ash-pit before the fire was drawn.

(5). *Sampling of fuel, ash and residual fuel.*—The fuel was sampled in the usual manner by taking a small portion from each firing. The sample so collected varied from about 5 per cent to 10 per cent of the total fuel fired. It was collected in a can with a closely fitting cover, and, within a few hours after the close of the test, was thoroughly mixed, crushed to $\frac{1}{4}$ in. size or smaller, and quartered until a 1000 gram sample was obtained. This 1000 gram sample, placed in a suitable pan, was air-dried and then transferred to the Chemical Laboratory in glass jars for the purpose of chemical analysis.

The ash and residual fuel were each run through a laboratory crusher reducing them to pieces $\frac{1}{4}$ in. or smaller. They were then quartered, accompanied with thorough mixing, until samples were obtained of each, which would about fill a one quart glass jar.

(6). *Chemical analyses.*—All chemical analyses were made at the chemical laboratories of the University of Illinois. Proximate analyses and calorific determinations of the fuel were made for each test or for each group of two tests, where the two boilers were operated simultaneously upon the same fuel. The ash and residual

for each test were analyzed for carbon and earthy matter. Ultimate analyses were made from composite samples for each fuel tested. The composite samples were made by combining from each of the air-dried samples an amount proportional to the fuel burned as represented by each sample. Calorific determinations were made in a Mahler-Atwater oxygen calorimeter. In Table 12, page 70, will be found analyses of the ash and residual fuel as to carbon and earthy matter, and the proximate analyses of the fuel for each test.

In Table 2 are given the proximate and ultimate analyses of the fuels as made from the composite samples.

TABLE 2
ANALYSES OF COMPOSITE SAMPLES
Per Cent

Kind of Fuel	Proximate Analysis Fuel as Fired				Ultimate Analysis Dry Fuel					
	Fixed Carbon	Volatile	Moisture	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash
Anthracite	77.68	7.07	3.47	11.78	81.33	2.12	1.82	0.91	1.61	12.21
Pocahontas	73.43	19.50	1.90	5.17	84.20	4.79	3.61	1.14	1.00	5.26
Gas House coke	81.74	2.74	5.73	9.79	86.05	0.83	0.41	0.91	1.41	10.39
Solvay coke	85.76	2.45	1.51	10.28	86.84	0.58	0.28	1.21	0.65	10.44
Illinois, Williamson county	48.42	36.28	6.66	8.64	71.62	5.19	10.29	1.53	2.11	9.26
Illinois, Macon county	40.56	37.67	10.01	11.76	66.98	4.63	10.34	1.42	3.56	13.07
Illinois, Vermilion county	40.35	39.57	11.14	8.94	73.22	4.43	8.29	1.52	2.48	10.06

TABLE 3
AVERAGE PROXIMATE ANALYSES OF FUEL AS FIRED
Per Cent

Kind of Fuel	Fixed Carbon	Volatile Matter	Combustible (Carbon + Volatile)	Moisture	Ash	Sulphur	Calorific Value B. t. u. per lb.
Anthracite	78.55	5.77	84.32	3.93	11.75	1.17	12682
Pocahontas	73.33	19.49	92.82	2.01	5.17	0.98	14753
Gas House coke	80.68	3.34	84.02	5.92	10.06	1.15	12053
Solvay coke	85.80	2.14	87.94	1.60	10.46	0.65	12505
Illinois, Williamson county	48.07	36.27	84.34	6.55	7.27	2.09	12275
Illinois, Macon county	40.84	37.56	78.40	10.24	11.36	3.19	11005
Illinois, Vermilion county	40.36	39.53	79.89	11.18	8.93	2.21	11546

Table 3 gives values for the proximate analyses of the different fuels obtained by averaging the values for all tests with each fuel. The averages included in this table are computed by giving weights to the values for each test proportional to the weight of fuel fired. A comparison of the average values for each fuel, as contained in this table, with the corresponding values of the proximate analyses made upon the composite samples exhibits some differences which are, however, for the most part, small. The average calorific value, determined for each fuel in the same manner as the other averages has been included in Table 3.

(7). *Feed water.*—The feed water delivered to each boiler through the measuring tanks was condensation from heating coils, and the effort was made to feed the water at as nearly constant a rate as possible, and at a temperature which might correspond fairly well with that of the returns in house-heating work. The feed water temperature averaged about 175° F.

(8). *Loading.*—For all tests a load equivalent to about 65 per cent of the boiler rating was maintained by means of a suitably sized orifice in the outlet. The evaporation of 0.3 lb. of water from and at 212° F. was assumed as equivalent to serving one sq. ft. of radiation for one hour. A pressure of 5 lb. controlled by the automatic regulators, which are a part of the boilers, was maintained at the boiler. The pressure after leaving the boiler was reduced to slightly over 2 lb. in the receiver, so that a difference of 2 lb. pressure was maintained between the two sides of the orifice. Recording gages were used in order that the variations in boiler pressure might be readily observed during the course of the test.

(9). *Temperatures.*—A recording pyrometer was used in connection with most of the tests made upon Boiler D₁, for the purpose of taking flue gas temperature. For the remainder of the tests upon boiler D₁, and for all tests upon D₂, mercury flue gas thermometers reading to 1000° F. were employed. A recording thermometer for outdoor temperatures was also employed.

(10). *Smoke and flue gas analyses.*—Smoke records were taken for each test, generally for a period extending from the time of one firing to the time of the next firing. The flue gas samples were, as a rule, taken as continuous samples, each over an interval of time of one hour. At times continuous samples were taken

extending over the entire time between two firings. These samples were analyzed in an Orsat apparatus of the common type.

(11). *Cleaning flues.*—The boiler flues were cleaned previous to each test in order that conditions in this respect might be approximately equal. On account of the preliminary fire, there was doubtless always some soot on the flues at the start of the test proper, as it was not considered advisable to open up the boiler for cleaning just before starting the new fire. Also the flues, doubtless, became coated with soot more rapidly with some fuels than with others. There would also, as a general rule, be a greater accumulation of soot and ashes in the flues for a sixteen or twenty-four hour test than for an eight hour test.

(12). *Miscellaneous observations.*—The following observations were taken every twenty minutes: height of water in the boiler, height of water in the feed tank, height of water in gage glass of separator, temperature of feed water, boiler room temperature, steam pressure in boiler, difference of pressure on the two sides of the orifice plate, and drafts in ash-pit, over the fire and in the flue.

6. *Test Data*

The test data were, in general, recorded in accordance with the requirements of the A. S. M. E. code and were entered upon blank forms suitably arranged for the class of work in hand.

On pages 84, 85, 86, and 87, of Appendix A will be found, Fig. 18-21, graphical logs of four tests which have been selected as representative. They are, respectively, records of tests made with anthracite, Pocahontas coal, coke and Illinois coal.

7. *Tabulated Data and Results*

In Appendix A, Table 12, will be found the principal data and results of the 48 tests under consideration; explanatory matter concerning the results accompanies the table. This material will be found upon pages 66 to 83, inclusive, of Appendix A.

In Tables 13 and 14, pages 88 and 89 of Appendix A, will be found data relative to flue gas analyses. It will be noted that the per cent of CO_2 is in general quite high. In all flue gas analyses the per cent of CO was also determined in the manner usual with the Orsat apparatus. Owing to the uncertainty as to the value of such determination these data are not here presented. In general no trace of CO was found or only a fraction of 1 per cent.

In one case, however, where the sample was taken immediately after firing, 4.3 per cent CO was found.

8. *Method of Calculating Results* The results tabulated in Table 12, Appendix A, are in general calculated by methods which are the same as those employed in calculating boiler trials made under the A. S. M. E. code.

Throughout all calculations involving capacity the evaporation of 0.3 pounds of water from and at 212° F. has been used as equivalent to serving one square foot of radiation for one hour.

In the calculation of item 23.2 tabulated on page 72, which is the total dry fuel fired minus the dry fuel equivalent of the ash and of the residual fuel, it was assumed that the ash and the residual fuel consisted of earthy matter and carbon only. The carbon found in the ash and the residual fuel by analysis was assumed to have a heating value of 14600 B. t. u. per lb. and was converted to dry fuel by dividing the total number of B. t. u. so found by the B. t. u. value of one pound of dry fuel under consideration.

9. *Discussion of Results*

A. *Efficiency and Evaporative Performance*

(1). *Efficiency and fixed carbon content.*—An examination of item 62 as given in Table 12, page 82, shows that the plant efficiencies varied from 44.76 per cent to 66.21 per cent. In Fig. 1 these efficiencies have been plotted for each test to a base, expressed in per cent, of the fixed carbon content of the coal. These points fall into two groups due to the low fixed carbon content of the Illinois coals as compared with the other fuels. The tendency of low efficiency to go with low fixed carbon content is, however, marked, and emphasizes the fact that in this respect the fuels high in fixed carbon content are much better adapted to present methods of house-heating. The Illinois coals may be considered as the natural fuel supply for this state and section and the problem becomes one of adapting methods and equipment to the burning of these coals at efficiencies at least approximating those of fuels like anthracite and coke.

(2). *Efficiency with Pocahontas coal.*—The lowest plant efficiencies recorded are for tests made with Pocahontas coal. The average plant efficiency with Boiler D₁ for this fuel was 44.97 per cent and with Boiler D₂ 55.43 per cent. A partial explanation of

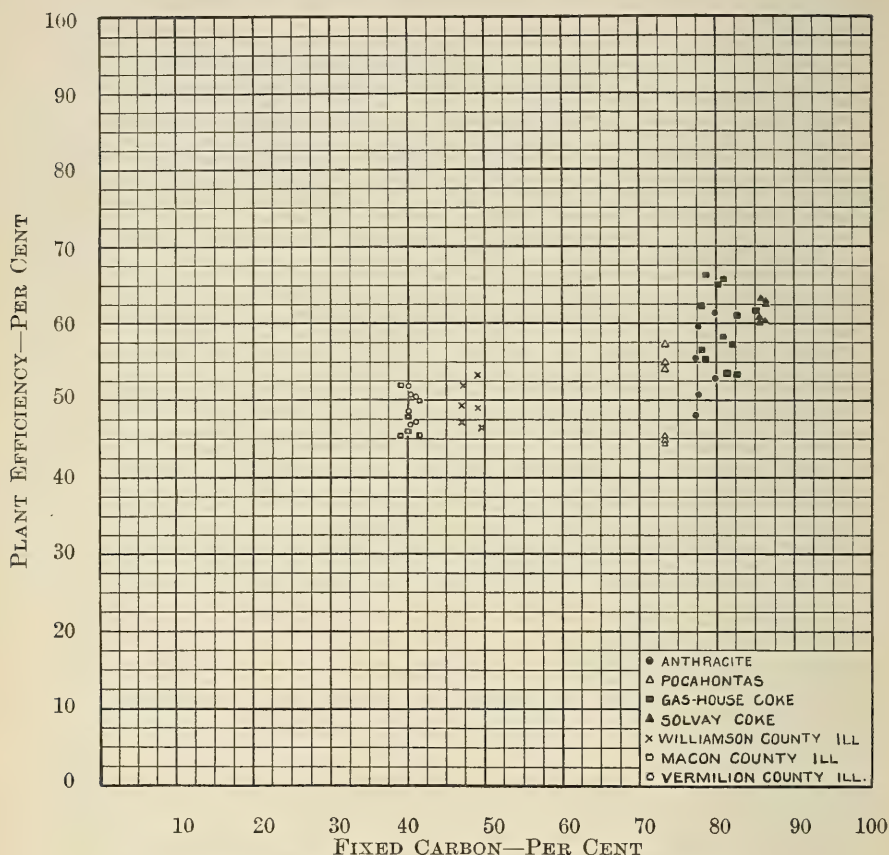


FIG. 1 RELATION OF EFFICIENCY TO FIXED CARBON

these low plant efficiencies for the Pocahontas coal is to be found in the fact that a comparatively large amount of unconsumed fuel passed through the grate with the ash. The per cent of carbon in the ash for Pocahontas tests varied from 50 to 70 per cent, being much higher than with any other fuel tested. The Pocahontas coal used contained a large amount of very fine coal which is the usual condition of this fuel in this market.

The efficiency of the boiler and furnace alone, excluding the effect of coal dropping through the grate, is, however, also low in the case of the Pocahontas coal. These efficiencies will be found under item 61, Table 12, page 82 and average values of the same in Table 6, page 36. The use of Pocahontas coal for

house-heating purposes is quite common in this section and when used is generally highly thought of for such work, having merits that may warrant its use in spite of low evaporative efficiency. Of the several fuels tested it has the highest heat content as expressed in B. t. u. contained. The small number of tests here reported precludes the possibility of drawing definite conclusions in regard to the efficiency that may be obtained with this fuel under the various conditions under which it may be consumed, while the wide variation in the efficiencies obtained, especially as between the two boilers, indicates the possibility of adapting fire conditions and equipment to the requirements of the fuel in order to obtain higher efficiencies.

(3). *Efficiencies of the two types of boilers.*—There has been no attempt in this article to compare or discuss the merits of the boilers used in making the tests, the tests having been conducted with the idea of comparing the fuels rather than the apparatus. In the case of Pocahontas coal, as mentioned above, it was found that one boiler was operating much more efficiently (measured by evaporation) than the other. When testing the two kinds of coke it was found that in the case of the Solvay coke the efficiencies for the two boilers were not greatly different, while when testing with the gas-house coke they differed greatly. It will be noted that in the tests reported there are six tests with each fuel except in the case of the gas-house coke, with which fuel twelve tests were made. The series of tests upon the gas-house coke was duplicated as a check in regard to this difference in performance. The coke was chosen as being a fuel with which constant fire conditions could be readily maintained and with which any discrepancy would be most easily detected, although the difference in efficiency as between the two boilers was the most marked in the case of Pocahontas coal. The second set of tests with the gas-house coke did not show material differences in regard to efficiencies from those shown by the earlier tests. The principal difference between the two cokes, aside from a slightly higher volatile content in the gas-house coke was the smaller and much more uniform size to which the Solvay coke was crushed. Fire conditions were much more uniform when burning the Solvay coke and it seems probable that efficiencies were much more affected by varying chemical or physical characteristics of the fuel in the case of the boiler with the comparatively small amount of heating surface.

(4). *Variations in efficiency.*—Efficiencies as determined by fuel tests with house-heating boilers apparently vary greatly with varying conditions of fuel and fire and should be compared only with the greatest care. Omitting considerations which relate to the boiler and furnace employed, the composition of the fuel is probably the most important factor to be considered. A coal high in fixed carbon so that combustion may be completed on or near the grate will give high efficiencies, a coal high in volatile matter which, when burning, gives off large volumes of rich gases that may or may not be burned, will give low efficiencies. The high volatile fuels are, as a rule, of approximately the same calorific capacity as the high carbon fuels, while if based upon the cost per B. t. u. they are much cheaper. The problem in this particular respect (not considering cleanliness, control, etc.) then becomes one of determining the conditions which will permit of burning the high volatile coals at efficiencies at least approximately equal to those of the high carbon coals, or stated somewhat differently, the conditions which will permit of burning Illinois coal, the cheap and natural supply, instead of the fuels which must be transported long distances and sold at correspondingly high prices. For the tests here considered it is believed that decided differences in efficiency were caused by various fire conditions due to the size of fuel burned and to the per cent of fine material contained therein, to the degree with which the fire bed coked, burned evenly over the grate or burned holes through and around itself, also to the extent to which the gases first distilled from a fresh charge of fuel were burned or passed away unconsumed. While efforts were made throughout the tests to keep fire conditions uniform, it not being the purpose of the tests to study efficiency under varying conditions, such variations as did occur point to the possibility of improving efficiency by proper attention to details relating to fuel, operation and equipment.

(5). *Efficiencies as compared with those of power boilers.*—Under conditions comparable to the tests made efficiencies ranging from 40 per cent to 70 per cent may be expected. These efficiencies are somewhat, though not greatly, lower than corresponding figures upon power boilers.

(6). *Illinois coal.*—The efficiencies obtained indicate the desirability of improvement in order that Illinois coal may be placed

more nearly on an equal footing with other fuels in this respect when employed for house-heating purposes.

(7). *Evaporative performance.*—The equivalent water evaporated from and at 212° F. per sq. ft. of heating surface varied in the case of boiler D₁ from 3.36 lb. to 3.91 lb. and in the case of boiler D₂ from 2.48 lb. to 2.89 lb. If these small boilers were rated upon 10 sq. ft. of heating surface to 1 b. h. p., which is equivalent to an evaporation of 3.45 lb. per sq. ft., when operating at 100 per cent capacity, then boiler D₁ under the test conditions was evaporating water at quite as high a rate as is usual in power boiler work, while boiler D₂, owing to its greater heating surface, was evaporating water at a somewhat lower rate, but still at one which is by no means uncommon in ordinary power boiler work. When it is remembered that these boilers were operating at approximately 65 per cent of their rated capacity it will be seen that high rates of evaporation would be required if they were operated at 100 per cent rated capacity, or if forced to an overload. The variable demand upon the house-heating boiler will at times necessitate very high or very low rates of evaporation per square foot of heating surface, and the nature of the service may readily warrant somewhat inefficient performance under these conditions in order that the equipment be comparatively small, simple in construction and easily operated. It would appear, however, that a rate of evaporation much higher than has been found economical or advisable in power boiler work should also be avoided in house-heating boiler work if that be possible, and the effort should be made to so adapt the fuel and equipment that a rate of evaporation would be obtained which under average operating conditions would be most apt to be accompanied by high efficiency.

(8). *Average operating conditions.*—The conditions under which house-heating boilers operate are so varied that it is impossible to state any given per cent of their rated capacity as even approximately that of average operating conditions. A boiler used for heating an office building, school house, or in work of a similar character might be operated at a relatively high average capacity as high or higher than 65 per cent as obtained in the tests under consideration, while in residence work on a small scale a boiler may only be required to operate at a high capacity for a few hours each day and the average load may not be more than 20 per cent of the rated capacity.

(9). *Efficiency and capacity.*—The arrangement and amount of heating surface advisable for low capacities may be unsuited for high capacities and deductions in regard to any particular feature of house-heating boiler performance must be made with regard for such conditions. The tests here considered have all been run at practically one capacity (65 per cent of the rated capacity) and give little information in regard to efficiency as affected by varying capacity. The uniformly lower efficiency of boiler D₁ as compared with boiler D₂ with the corresponding high evaporation per square foot of heating surface would indicate that high rates of evaporation per square foot of heating surface due to reduced heating surface tend toward low efficiency at least in the neighborhood of the capacities at which the tests were run. A series of tests is now under way operating these boilers at capacities varying from about 10 per cent to 100 per cent of their rated capacity in order to throw further light upon the relation of efficiency to capacity. The rated capacities of D₁ and D₂, 800 and 1075 square feet of radiation, respectively, are closely proportional to the fuel capacity of the fire-boxes, while the ratio of capacity (expressed in square feet of radiation) to the total heating surface is much higher in the case of boiler D₁ than of D₂, that is, when operating at full capacity one square foot of heating surface in boiler D₁ must serve 18.2 square feet of radiating surface while for boiler D₂ one square foot of heating surface serves only 14.2 square feet of radiation. The ratio of direct to total heating surface is higher in the case of D₁ than of D₂.

B. Length of Tests and Method of Conducting

In order to determine what length of test was best in order to secure data of a satisfactory character, tests of eight, sixteen, and twenty-four hours were run with each fuel upon each boiler. The principal item affected by the length of the test is the amount of fuel consumed, which in turn affects many of the other important calculated items. The difficulties attending the determination of the amount of fuel consumed have been discussed and the manner in which the longer test tends to eliminate the errors which occur.

(1). *Fuel consumption.*—Fig. 2-5, pp. 27-30, show the coal as fired, plotted on a time base, for each test made with four of the fuels tested. In all cases the slope of the coal

line representing the period of the first charge of fuel is steeper than the slope of the line of subsequent firings. This is particularly marked in the case of the anthracite. An examination of the line

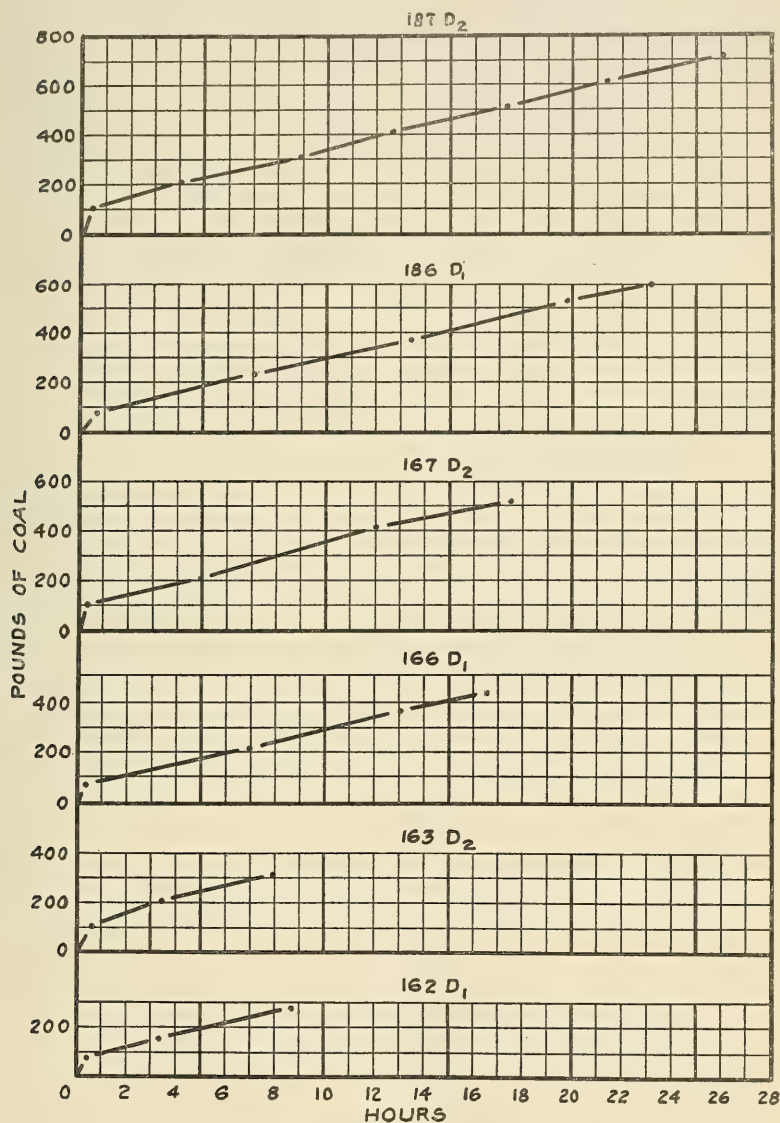


FIG. 2 FUEL CONSUMPTION—ANTHRACITE COAL

representing the second firing will in some cases disclose the fact that some unconsumed fuel remained in the fire-box at the time of the second firing and was then burned, making that period somewhat longer than subsequent periods. The time of the last

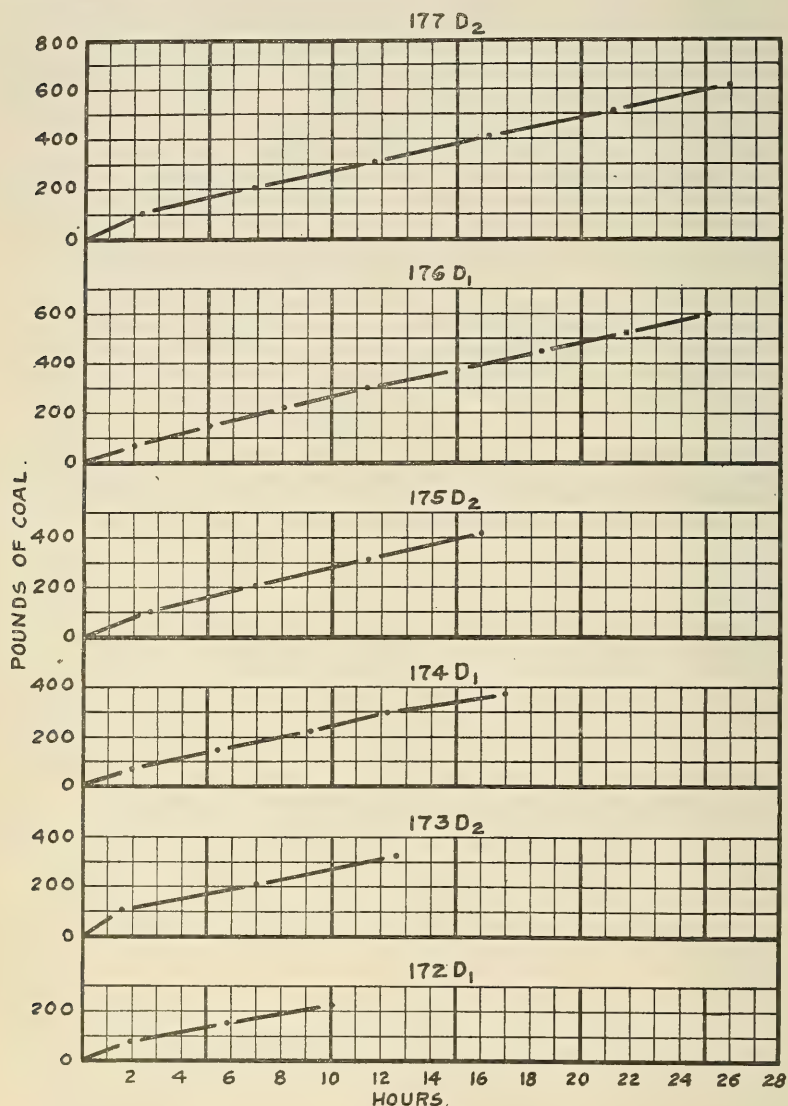


FIG. 3 FUEL CONSUMPTION—POCAHONTAS COAL

firing will also be noted as often being longer than the preceding periods on account of the fire being allowed to burn out somewhat more completely at the end of the test than was usual at the end of the other firing periods. As a rule, however, after the first firing the slope of the coal line is quite uniform, and it was the general opinion of the observers that after the first or second

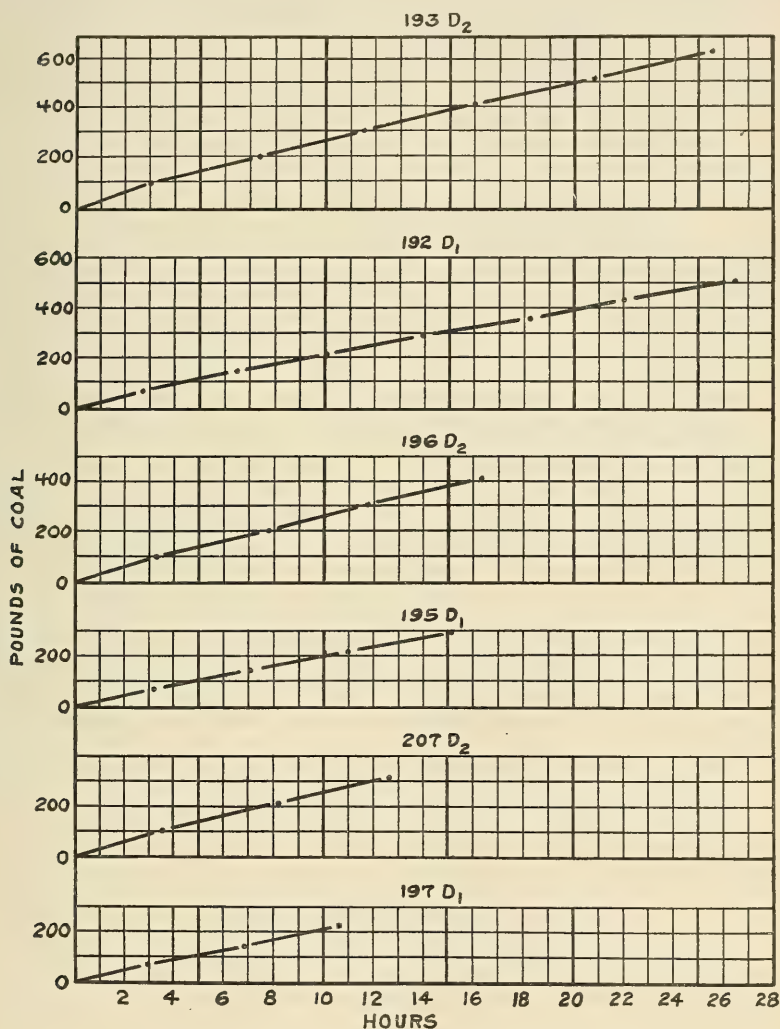


FIG. 4 FUEL CONSUMPTION—SOLVAY COKE

firing period the test conditions could readily be kept practically uniform for any reasonable length of time. At the beginning of this series of tests it was thought possible that after making the

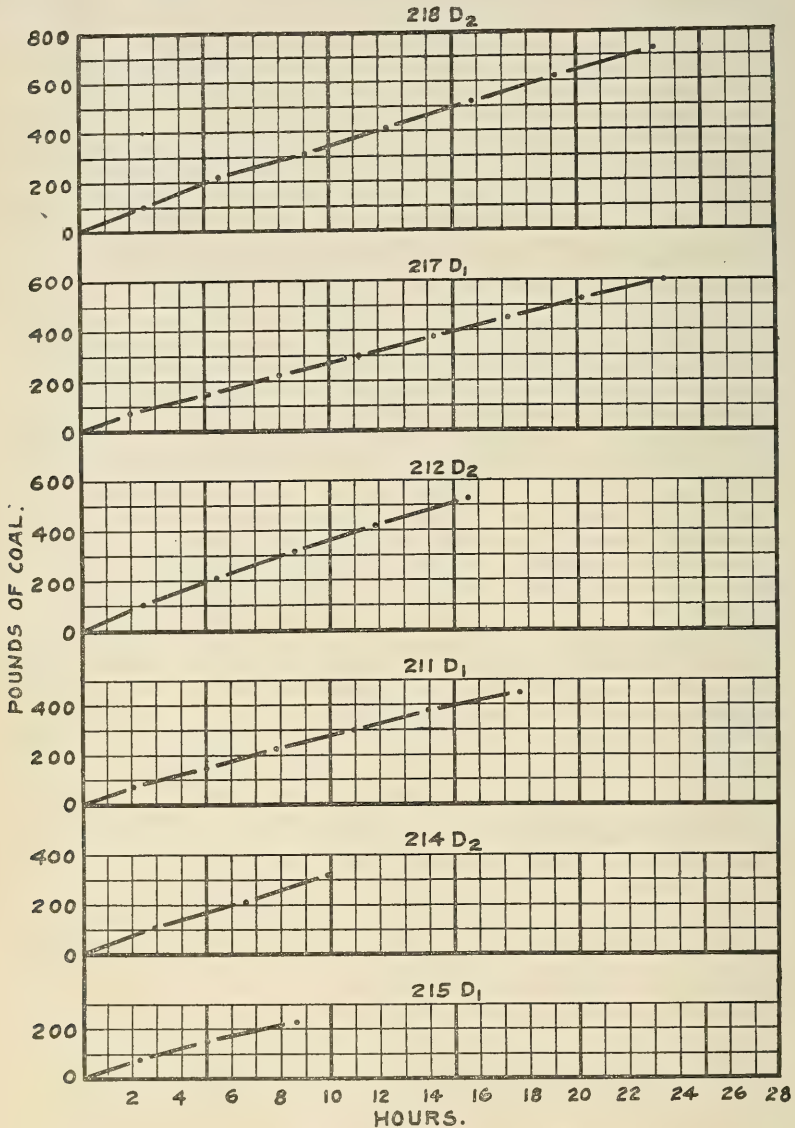


FIG. 5 COAL CONSUMPTION—ILLINOIS COAL (WILLIAMSON CO.)

tests, starting and stopping by the method adopted, it might be possible to divide the data so as to omit one or more of the firing periods, such as the first, or first and last periods, retaining only those periods as a portion of the test during which conditions were apparently constant. This would in effect give a test using the alternate method of starting and stopping. It has, however, not been thought advisable to attempt such a division of the data and discussion of it here. Many of the tests consisted of but three or four firing periods and the elimination of one or more periods would make the duration of the test extremely brief and correspondingly magnify errors due to the varying fire conditions. The methods adopted for determining the amount of fuel consumed were found to be very satisfactory and it seemed that little or nothing was to be gained by discussing the data upon a basis which might give less accurate values for that important item.

(2). *Efficiency and evaporation as affected by length of test.*—

Table 4 shows the equivalent evaporation and efficiencies for all tests, grouped as tests 8, 16 and 24 hours long. The same data are plotted in Fig. 6 and 7. In the majority of the tests the rates of evaporation and efficiencies are higher for the 16-hour tests than for the 8-hour tests. This condition is true to a more marked extent in the case of boiler D₁ than of boiler D₂. The lower efficiencies, in general, of the 8-hour tests may be due to losses incurred through inefficient burning during the first fire which would affect the results of the shorter tests to the greater extent. Accumulations of soot in the flues of boiler D₂ and the extent to which this soot was burned out during the tests may have affected efficiencies to a considerable extent. Comparing the rates of evaporation and efficiency for the 16-hour and 24-hour tests the differences are in general not so great as between the 8 and 16-hour tests.

No complete explanation is here offered as to the cause of this variation in the matter of efficiency and rate of evaporation per pound of fuel for tests of different length. In some individual tests varying conditions which were noted were thought to have caused these changes either in part or altogether, but no general conclusion in this respect could be drawn. It was, however, considered that 16-hour tests would give results more reliable and better for comparative purposes than 8-hour tests and that as be-

TABLE 4

EQUIVALENT EVAPORATION AND EFFICIENCY FOR DIFFERENT LENGTHS OF TESTS

	8-hour Test			16-hour Test			24-hour Test		
	Length of Test	Equivalent Evaporation Per Pound of Fuel as Fired	Efficiency of Plant	Length of Test	Equivalent Evaporation Per Pound of Fuel as Fired	Efficiency of Plant	Length of Test	Equivalent Evaporation Per Pound of Fuel as Fired	Efficiency of Plant
	hours	pounds	per cent	hours	pounds	per cent	hours	pounds	per cent
BOILER D1									
Anthracite.....	8.77	6.32	48.07	16.55	6.67	50.58	23.15	6.68	52.59
Pocahontas.....	10.07	6.84	44.76	17.03	6.90	45.18	25.13	6.87	44.98
Gas House Coke.....	8.43	6.65	53.43	15.83	6.74	53.33	23.70	7.08	56.46
Gas House Coke.....	9.57	6.69	55.23	17.15	7.15	57.26	26.23	7.19	58.16
Solvay Coke.....	10.63	7.75	60.47	15.17	8.02	62.58	26.53	7.85	60.32
Illinois, Williamson county.....	8.63	5.86	46.42	17.68	6.05	47.17	23.48	6.19	48.99
Illinois, Macon county.....	9.78	5.19	45.46	16.73	5.24	45.94	24.58	5.18	45.53
Illinois, Vermilion county.....	7.97	5.53	46.88	16.45	5.78	47.14	24.47	5.73	48.50
BOILER D2									
Anthracite.....	8.00	7.26	55.22	17.52	7.87	59.68	26.00	8.01	61.23
Pocahontas.....	12.65	8.25	53.99	16.05	8.38	54.87	25.93	8.77	57.42
Gas House Coke.....	11.85	8.02	66.21	15.55	7.99	61.51	24.85	8.12	65.69
Gas House Coke.....	11.70	7.99	65.05	14.92	7.72	61.08	24.17	7.80	62.20
Solvay Coke.....	12.58	8.29	63.27	16.32	8.11	63.28	25.55	7.87	60.47
Illinois, Williamson county.....	9.88	6.61	51.93	15.58	6.33	49.35	23.18	6.73	53.26
Illinois, Macon county.....	8.38	5.93	51.95	16.03	5.48	48.04	23.13	5.71	50.18
Illinois, Vermilion county.....	8.55	5.97	50.61	15.07	6.18	50.40	25.02	6.12	51.80

tween tests 16 and 24 hours long the results of the shorter tests would in general be as serviceable as those of the longer ones.

(3). *Length of test required.*—Basing a conclusion as to the length of test desirable upon the work here reported for tests which are comparable to these tests as to load conditions, that is, operating at fairly high capacity, as 50 per cent or more of rated capacity, it would seem advisable to make the test at least 16 hours long and to have at least three firing charges. The stop should be made according to fire conditions, rather than at the

end of a given interval of time. In case the firing charges were large or the load light, the length of the test might with advantage be somewhat longer than 16 hours. The length of 16 hours is given as approximately the minimum time which would give results that could be considered as satisfactorily comparable. Under the test conditions the 8-hour tests were liable to be considerably affected by the varying fire conditions at the start and stop of the test, while it seemed that after about 16 hours little was gained by running the test through 24-hour or longer periods. It is likely, however, that for service tests with very variable

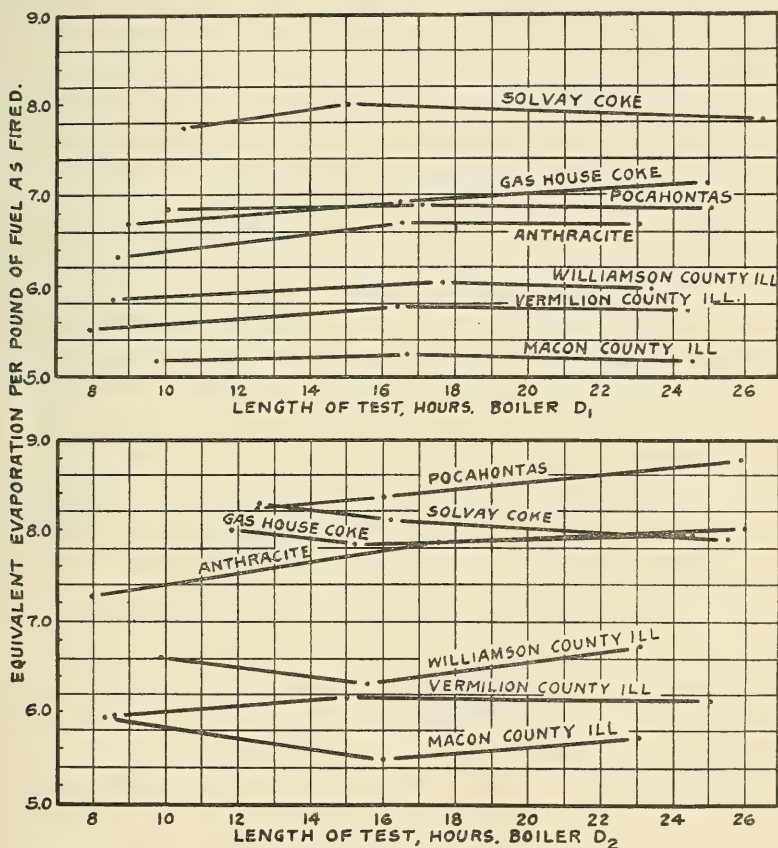


FIG. 6 RELATION BETWEEN LENGTH OF TEST AND EQUIVALENT EVAPORATION PER POUND OF FUEL AS FIRED

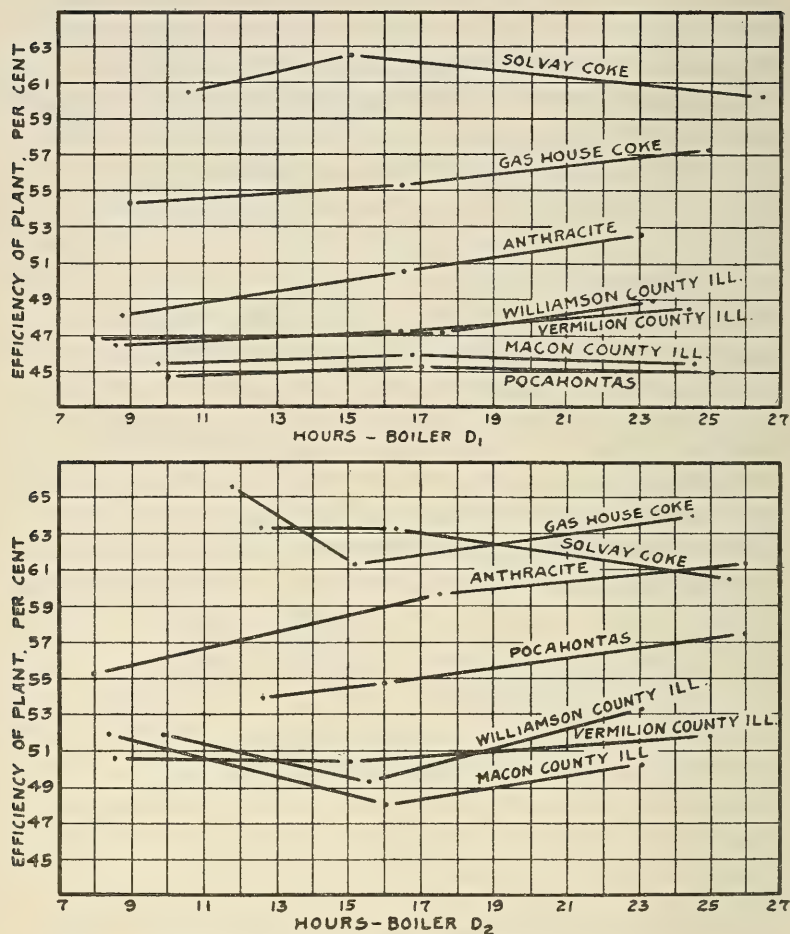


FIG. 7 RELATION BETWEEN PLANT EFFICIENCY AND LENGTH OF TEST

loading and operating at low average capacity, a test of 24 hours or longer will be found desirable.

C. Fuel Cost

(1). *Price and heating value.*—The great advantage of Illinois coal for the Illinois user and others within a reasonable distance of the field is in its low price. First-class Illinois coal for domestic purposes can be purchased for one-half or less than one-half the price which must be paid for anthracite. While the heating

TABLE 5
RELATIVE COST OF FUELS

Kind of Fuel	B. t. u. per Pound of Fuels as Fired	Cost of 14600 B. t. u. cents	B. t. u. per 1 cent	Cost of 14600 B. t. u. Based on Anthracite as 100% (per cent)	B. t. u. in per cent Based on Anthracite as 100%	Cost per Ton of 2000 lbs. in Local Market	Cost in per cent Based on Anthracite as 100%
Anthracite.....	12682	0.47	30417	100	100	\$8.25	100
Pocahontas.....	14753	0.27	54073	57.4	116.3	5.50	66.6
Gas House Coke.....	12053	0.30	48667	63.8	95.0	5.00	61.0
Solvay Coke.....	12505	0.35	41714	74.5	98.6	6.00	72.7
Illinois, Williamson county.....	12275	0.22	66364	46.8	96.8	3.75	45.5
Illinois, Macon county.....	11005	0.23	63478	48.9	86.8	3.50	42.4
Illinois, Vermilion county.....	11546	0.18	81111	38.3	91.0	2.85	34.5

value of the anthracite and other high-priced fuels is in general greater than the Illinois coals, the difference is not so great as to be in any sense commensurate with the difference in price. Table 5 gives information concerning the relative cost of the fuels tested. The heating value of the Pocahontas coal is considerably higher than the other fuels, that of the anthracite somewhat higher than the Illinois coal, while the cokes have approximately the same heating value as the highest given for the Illinois coal. It will be noted that the B. t. u. (British thermal units) per pound of anthracite is 12682 as compared with a value of 12275 for a comparatively high-priced Illinois coal and a value of 11546 for a somewhat cheaper Illinois coal. In one case the Illinois coal costs 45.5 per cent of the price of the anthracite and contains 96.8 per cent of its heating value. In the other case the Illinois coal costs but 34.5 per cent of the price of the anthracite and contains 91 per cent of its heating value. While it is recognized that under present conditions the heat content alone is by no means a sufficient measure of the value of the coal, this great discrepancy in price per heat unit suggests the need of improvement in the methods of burning the cheaper fuel. If all other advantages or disadvantages could be equalized or eliminated, the B. t. u. delivered by the fuel would be the direct measure of its value.

(2). *Relative cost as shown by tests.*—Table 6 presents comparisons relative to fuel costs. The values tabulated in Columns 6 to 13 inclusive are averages for all tests run with each fuel with each boiler. Columns 1 and 2 give the kind and cost of each fuel.

TABLE 6 COMPARISON OF FUEL COSTS

1	2	3	4	5	6	7	8	9	10	11	12	13
Kind of Fuel	Cost of Fuel per Ton of 2,000 lbs.	Calorific Value of B. t. u. per Pound Fuel as Fired	Cost per 14,600 B. t. u.	Cost per Pound of Fixed Carbon	Percent of Builders Rating Developed	Fuel as Fired per sq. ft. of Grate Surface per hour	Equivalent Evaporation from and at 212° F. per hour per sq. ft. of Heating Surface	Cost of Evaporating 1000 lbs. of Water from and at 212° F.	Percent Cost of Evaporating 1000 lbs. of Water from and at 212° F. Based on Cost of Anthracite as 100 Percent	Percent Saving of Cost of Anthracite	Cost of Fuel per 100 sq. ft. of Radiating Surface per hour	Efficiency of Plant [Boiler Furnace and Grate]
	dollars	B. t. u.	cents	cents	per cent	lb.	lb.	cents	per cent	per cent	cents	per cent
BOILER D1												
Anthracite.....	8.25	12632	0.47	0.53	66.00	5.6	3.63	62.37	100	0	1.87	50.41
Pocahontas.....	5.50	14753	0.27	0.38	63.88	5.2	3.51	40.04	64.2	35.8	1.20	44.97
Gas House Coke.....	5.00	12025	0.30	0.31	65.48	5.3	3.60	36.20	58.0	42.0	1.09	55.65
Solvay Coke.....	6.00	12474	0.35	0.35	64.46	4.7	3.54	38.10	61.1	38.9	1.14	61.12
Illinois, Williamson county.....	3.75	12266	0.32	0.39	64.04	6.0	3.51	31.09	49.8	50.2	0.93	47.53
Illinois, Macon county.....	3.50	11005	0.23	0.44	65.54	7.1	3.60	33.71	54.0	46.0	1.01	45.64
Illinois, Vermillion county.....	2.85	11532	0.18	0.35	65.13	6.2	3.59	25.14	40.3	59.7	0.76	47.51
BOILER D2												
Anthracite.....	8.25	13632	0.47	0.53	62.33	4.4	2.65	53.54	100	0	1.61	58.71
Pocahontas.....	5.50	14753	0.27	0.38	64.09	4.1	2.72	32.51	60.7	39.3	0.97	55.43
Gas House Coke.....	5.00	12076	0.30	0.31	62.48	4.2	2.66	31.50	58.8	41.2	0.95	63.62
Solvay Coke.....	6.00	12531	0.35	0.35	60.78	4.0	2.58	37.08	69.3	30.7	1.12	62.34
Illinois, Williamson county.....	3.75	12284	0.22	0.39	64.81	5.3	2.75	28.61	53.4	46.6	0.86	51.51
Illinois, Macon county.....	3.50	11005	0.23	0.44	65.74	6.2	2.79	30.70	57.3	42.7	0.92	50.06
Illinois, Vermillion county.....	2.85	11543	0.18	0.35	65.30	5.8	2.77	23.40	43.7	56.3	0.70	50.94

These were purchased mostly from local dealers and have already been described in the paragraph on fuels on page 14. Almost all of these fuels can be purchased somewhat more cheaply in larger quantities. Column 3 gives the heating capacity per pound for each fuel as taken from Table 3, page 18 and Column 4 the cost of 14600 B. t. u. as purchased in each. (The number 14600 B. t. u. as the calorific value of a pound of pure carbon is taken as a convenient unit for comparison.) In Column 5 is given the cost per pound of fixed carbon for the different fuels. Columns 6, 7 and 8 give three of the principal operating conditions inserted here for convenience in making comparisons and in showing the degree of uniformity of these conditions. Columns 9, 10 and 11 give the fuel cost of evaporating 1000 lb. of water from and at 212° F. and percentage relations concerning the same. Column 12 also presents the results relative to fuel cost and evaporation stated in terms of serving 100 sq. ft. of radiation. Column 13 gives averages of plant efficiencies.

(3). *Cost per B. t. u. and per pound of fixed carbon.*—It will be noted that the cost per B. t. u. is almost three times as much in the case of anthracite as in the cheapest of the Illinois coals. When comparing the costs per pound of fixed carbon, which under present conditions of burning is a very important consideration, the differences in price are not as marked, the cokes having the lowest cost per pound in this respect. It is to be supposed that the heat content of the fixed carbon is utilized to about the same extent for all the fuels, the variations in efficiency being largely due to incomplete utilization of the heat-content of the volatile matter. The relation of efficiency to fixed carbon content has already been shown graphically in Fig. 1, page 22. In Fig. 8 and 9 average efficiencies have been plotted with relation to cost per B. t. u. per cent volatile and per cent of fixed carbon. These figures show graphically the higher efficiencies obtained with the higher priced fuels, and those high in fixed carbon content, as contrasted with those high in volatile matter, and indicate the desirability of developing methods for burning the cheap and high volatile fuels in a more efficient manner.

(4). *Cost of evaporation*—The rate of combustion and rate of evaporation per square foot of heating surface are both lower in the case of boiler D₂ owing (aside from efficiency differences) to the greater grate and heating surfaces of that boiler relative to the

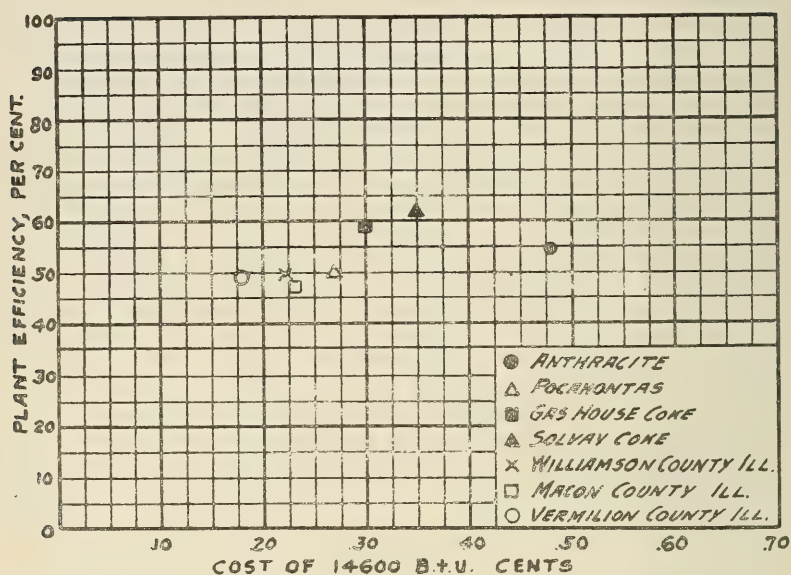


FIG. 8 RELATION BETWEEN PLANT EFFICIENCY AND COST OF 14600 B. T. U.

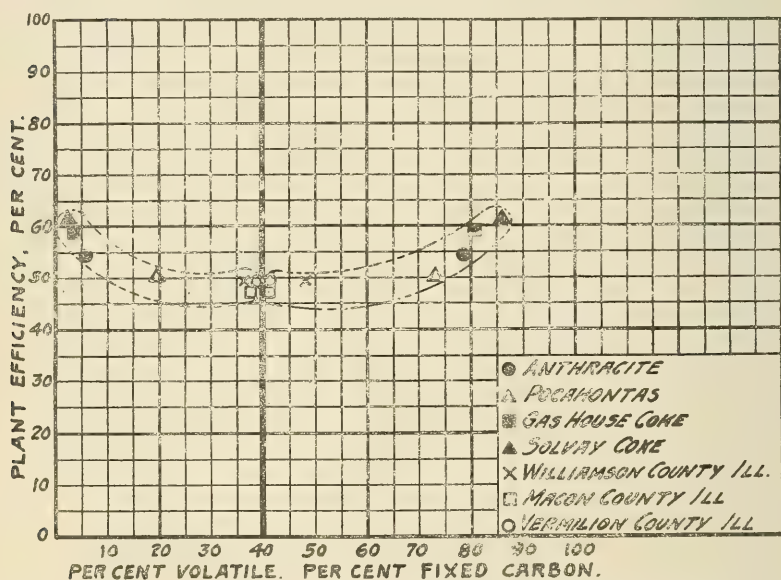


FIG. 9 RELATION OF EFFICIENCY TO PER CENT VOLATILE AND PER CENT FIXED CARBON

rated capacity. The cost of evaporating 1000 lb. of water from and at 212° F. varies from 62.37 cents for anthracite on boiler D₁ to 23.40 cents for the cheapest of the Illinois coal tested on boiler D₂. If evaporative performance alone be considered, this shows a saving of 62.5 per cent of the cost of the anthracite for the extreme cases noted. Considering each boiler separately the corresponding figures are savings of 59.7 and 56.3 per cent, respectively, in the case of boiler D₁ and boiler D₂. Similar differences as between anthracite and the other fuels, also between Illinois coals and the Pocahontas coal and the cokes, while not as great, are sufficient to warrant, other conditions being equal, the choice of Illinois coal on the ground of economy. The same percentage differences relative to fuel cost apply to the cost of serving 100 sq. ft. of radiation per hour as to the cost of evaporating 1000 lb. of water, and Column 12 merely presents in a slightly different manner the fact that as between the extreme cases of the tests considered the same heating effect was produced by one of the Illinois coals at 37.5 per cent of the fuel cost of the anthracite.

(5). *Relative fuel values as determined by tests.*—In Table 7 are presented relative values of the fuels tested. These values are based upon evaporative performance as determined under the test conditions and this fact should be borne in mind in comparing them. In the first part of the table the cost of evaporating 1000 lb. of water from and at 212° F. is shown for fuel prices ranging from \$1.00 to \$10.00 per ton for each fuel. Comparisons may be made in the following manner: if in a certain locality anthracite costs \$8.00 per ton and Williamson County, Illinois, coal cost \$4.00 per ton it will be seen that it will cost 56.21 cents to evaporate 1000 lb. of water with the anthracite and 31.84 cents to do the same work with the Illinois coal.

In the second part of the table the same relative values are given in a somewhat different manner. The relative values of the different fuels per ton are expressed in dollars with the price of anthracite ranging from \$1.00 to \$10.00 per ton. If, for example, in a given locality, anthracite costs \$8.00 per ton, Williamson County, Illinois, coal is (for evaporating purposes) worth \$7.03 per ton and if the Illinois coal can be bought for a less price than \$7.03 a saving can be made by using it instead of the anthracite. Again, if at a certain place Williamson County coal can be purchased for \$3.51 per ton then (for evaporative

TABLE 7

RELATIVE VALUE OF FUELS FOR USE IN HOUSE-HEATING BOILERS AS
DETERMINED BY EVAPORATIVE TESTS ON TWO TYPES OF
BOILERS WHEN OPERATED AT 65 PER CENT OF
THEIR RATED CAPACITY

Kind of Fuel	Cost in Cents of Evaporating 1000 pounds of Water from and at 212° F., with Price of Fuel Ranging from \$1.00 to \$10.00 per Ton of 2,000 pounds									
	\$1	\$2	\$3	\$4	\$5	\$6	\$7	\$8	\$9	\$10
Anthracite	7.03	14.05	21.08	28.11	35.13	42.16	49.19	56.21	63.24	70.27
Pocahontas.....	6.59	13.19	19.78	26.37	32.97	39.56	46.15	52.75	59.34	65.93
Gas House Coke.....	6.77	13.54	20.30	27.07	33.84	40.61	47.37	54.14	60.91	67.67
Solvay Coke.....	6.27	12.53	18.80	25.07	31.33	37.60	43.87	50.13	56.40	62.67
Illinois, Williamson county.....	7.96	15.92	23.88	31.84	39.80	47.76	55.72	63.68	71.64	79.60
Illinois, Macon county.....	9.20	18.40	27.60	36.80	46.00	55.20	64.40	73.60	82.80	92.00
Illinois, Vermilion county.....	8.52	17.04	25.55	34.07	42.59	51.11	59.63	68.15	76.66	85.18

Kind of Fuel	Relative Value of Fuels (Determined by Evaporative Tests) with Price Varying from \$1.00 to \$10.00 per Ton of 2,000 pounds of Anthracite									
	\$1	\$2	\$3	\$4	\$5	\$6	\$7	\$8	\$9	\$10
Anthracite	\$1.00	\$2.00	\$3.00	\$4.00	\$5.00	\$6.00	\$7.00	\$8.00	\$9.00	\$10.00
Pocahontas.....	1.07	2.14	3.21	4.28	5.35	6.42	7.49	8.56	9.63	10.70
Gas House Coke.....	1.04	2.07	3.12	4.15	5.19	6.23	7.27	8.31	9.35	10.39
Solvay Coke.....	1.12	2.23	3.34	4.46	5.58	6.69	7.81	8.92	10.04	11.15
Illinois, Williamson county.....	.88	1.76	2.64	3.51	4.39	5.27	6.15	7.03	7.91	8.79
Illinois, Macon county.....	.76	1.52	2.28	3.04	3.80	4.57	5.33	6.09	6.85	7.61
Illinois, Vermilion county.....	.82	1.64	2.46	3.29	4.11	4.93	5.75	6.57	7.39	8.21

purposes) anthracite is at that place only worth \$4.00 per ton and if more than \$4.00 must be paid for anthracite the additional amount must be considered as a loss or as being expended for advantages possessed by the anthracite such as cleanliness, and ease of fire control not possessed by the other fuel.

D. Control

Under the conditions of the tests little difficulty as to control or regulation was experienced. The observers were at all times present and gave such attention as was required to maintain the capacity desired. As already explained for these tests, questions relating to attention required, control and cleanliness were considered of secondary importance to obtaining tests comparable upon an evaporative performance basis. When burning the anthracite and the cokes, almost no attention was given the fire from one time of firing to the next. A preliminary adjustment of the chains operating the ash-pit damper and check was made

for each fuel if considered necessary and was in general not changed during the tests with that fuel. It was found advisable to keep the ash-pit as nearly air tight as possible except for the damper in the ash-pit door in order that the fire might be effectually checked when the damper was closed. This was found particularly desirable in the case of the quick burning Illinois coal. In general the attention required by the Pocahontas and Illinois coals was considerably more than that required by the anthracite and coke. The regulation was also much more uniform when burning the anthracite and coke than with the other fuels.

E. Smoke

In Table 15, page 90, Appendix A, are given data relative to the smoke produced. Smoke records were not taken at all times. For the majority of the tests a record was taken for only one firing interval, that is, from the time of firing one charge of fuel to the time of making the next charge, and no data are here tabulated except such as extend over such a complete interval. Smoke records taken during the first firing interval were affected by the smoke produced by the kindling used. This is particularly marked in the case of the Solvay coke as practically no smoke was produced with this fuel after the first firing. During the time of making smoke records, observations were made at one minute intervals while smoke was being produced and at somewhat longer intervals when it was known that no smoke was being produced. The smoke produced was often of a yellow or brownish color and difficult to compare by means of the Ringelmann color scale, also owing to several changes in the personnel of observers it is not to be expected that the observations are strictly comparable. It is believed, however, that they represent fairly well the smoke conditions as nearly as that can be done by the methods employed. In making and tabulating the smoke records the Ringelmann chart numbers 1, 2, 3, 4 and 5 were considered as representing 20, 40, 60, 80 and 100 per cent black smoke respectively.

F. Cleanliness

In matters of cleanliness in and about the boiler room, the anthracite and coke were superior to the other fuels. The total ash from the Pocahontas coal was comparatively small in amount, free from clinkers and easily handled. This also was true to a somewhat less extent for the anthracite and cokes, while the ash

from the Illinois coals contained more or less clinkers, was obtained in greater amount and was more troublesome to handle. Observations as to the thickness of the soot and ash collecting upon the walls of the flues were made at the end of the tests. These observations were incomplete and varied greatly as compared with each other and are not reported. For a number of the tests the soot which had collected in the flues was burned out during the tests while in other cases this did not happen. Owing to the arrangement of the flue surfaces with respect to the fire-pit this burning of the soot was much more apt to take place in boiler D₁ than in D₂.

G. General

In making fuel tests with house-heating boilers especially if it is desired to consider the boiler as well as the fuel being tested, it would seem advisable to test at approximately the average capacity at which the fuel and equipment are to be operated, or if the load demand is to be very variable, to test under conditions approximately similar to the operating conditions. If the boiler is to be used for heating purposes where the load demand will approach its rated capacity and be fairly constant over a considerable portion of the day, as might be the case in many comparatively large installations, tests under those conditions will give results as to efficiency, rate of evaporation, and other conditions which will be dependable and of value. On the other hand, tests run under conditions similar to those which might exist in a small residence, only requiring a hot fire for a few hours and an average load of possibly 20 per cent or 30 per cent of the rated capacity, would give results for the most part applicable only to like service conditions. This would necessitate tests of at least two general types, one of which would be quite similar to tests as ordinarily run upon power boilers, probably making evaporative performance the main item sought, and the other would be of the nature of a service test where much more relative attention would be paid to details concerning attendance, control, and cleanliness. Further tests which are now in progress with house-heating apparatus under various conditions as to capacity and service will, it is hoped, throw some further light upon the relations existing under widely varying service conditions.

In making a comparison of the fuels tested as to the advantages or disadvantages possessed by each, it is necessary to keep

in mind the conditions under which these particular tests were made. Other test conditions as to capacity or attendance might warrant in some respects quite different conclusions.

Several general observations may, however, be made. Considering the cost factor as expressed in the cost per ton of fuel, cost per heat unit and cost per unit of evaporation, the Illinois coal has so great an advantage over anthracite or high-priced eastern coals that it seems probable that this factor alone will in a very large number of cases and to an ever increasing degree bring about the use of the cheaper fuel. This condition will come about in spite of recognized disadvantages with regard to smoke, dirt and more or less troublesome fire control, and emphasizes the necessity of perfecting conditions, fuels, or equipment, so that these drawbacks may be eliminated or reduced to a minimum. Fire conditions and general cleanliness can be bettered through proper screening and sizing of the coal, probably through washing at the mines, and through improvements made upon the fuel burning equipment. Similar care and attention to the matter of details will also to a certain extent reduce the smoke given off. At present, however, it seems unlikely that we can hope to burn Illinois coal under average domestic conditions without producing an amount of smoke which must be both unsightly and injurious. Except for a limited number of localities where effective smoke abatement laws may be operative, these conditions with respect to smoke will doubtless continue to grow worse with the increasing use of this fuel. Sufficiently decided and immediate improvement in regard to smoke prevention when burning Illinois coal in these small units is hardly to be looked for, and the remedy would seem to be rather in central station heating work or in previous preparation of the fuel to render it smokeless. Central station heating is at present only to be considered under special conditions and can not be considered as a solution of the problem as a whole. The most important and at the present time practicable method of previously preparing the fuel is through its conversion into coke. Considering cost as illustrated by the tests made it would appear that coke is still at a considerable disadvantage with respect to the raw Illinois coal, not, however, to so great an extent as anthracite. Coke has the advantages of smokelessness and cleanliness possessed by anthracite, but upon the other hand is handicapped by certain disadvantages, such as its comparative

bulk, the non-suitability of a great proportion of the present heating apparatus to burn it to the best advantage, or in sufficient quantity under extreme weather conditions. Apparatus especially designed for burning coke will doubtless eliminate these difficulties to a large extent. Manufacturers of house-heating apparatus are at present offering equipment specially designed to meet this demand. Further, it is to be hoped that with the increased coke production, particularly the increased production from Illinois coal, there will come prices that will permit coke to compete favorably with the less clean fuels with respect to cost. The general use of coke as fuel for domestic purposes, and the consequent non-production of black smoke would eliminate a phase of the smoke problem which at present is both serious and difficult to handle. In a larger way also, the use of coke, as prepared for example by the Solvay or by-product process, appears to be in the direction of a solution of both the smoke problem and the problem of the economic use of the coal supply. Aside from the condition of blackness, due to unconsumed carbon, smoke contains other constituents, also injurious to both health and materials. The sulphur content, which in Illinois coal is relatively high, gives rise to one of the most injurious of such constituents. The proper preparation of Illinois coal for domestic use, whatever the process may be, should take out or reduce the quantity of injurious elements contained in the coal. The process of coal washing and the conversion of coal to coke are both beneficial in this respect and may be considered as steps in the right direction with regard to reducing the injury due both to the visible blackness of the smoke, and to the injurious constituents which occur, such as colorless gases.

In general, then, we may conclude: (1) that on the score of economy the high-priced eastern coals must give way to the cheaper home product; (2) that that product will be used in continually increasing quantities for domestic purposes; (3) that this condition will be accompanied by improved equipment and methods of burning the cheaper fuel; (4) that the use of raw Illinois coal will continue to be accompanied by a considerable amount of smoke and dirt which must eventually lead to some adequate method of preparing this fuel in order to eliminate this feature; (5) that the conversion of Illinois coal to coke offers, at present, a seemingly satisfactory method of such preparation;

and (6) that with the adaptation of equipment to satisfactorily burn coke at a price which will put it on an equal footing with raw coal, coke may be expected to take a very important place as a domestic fuel, and be an important factor in its relation to the smoke problem and the fuel question as a whole.

10. *Equipment*

These tests were conducted with two house-heating boilers installed by the Engineering Experiment Station at the University of Illinois. The boilers have been designated as boiler D₁

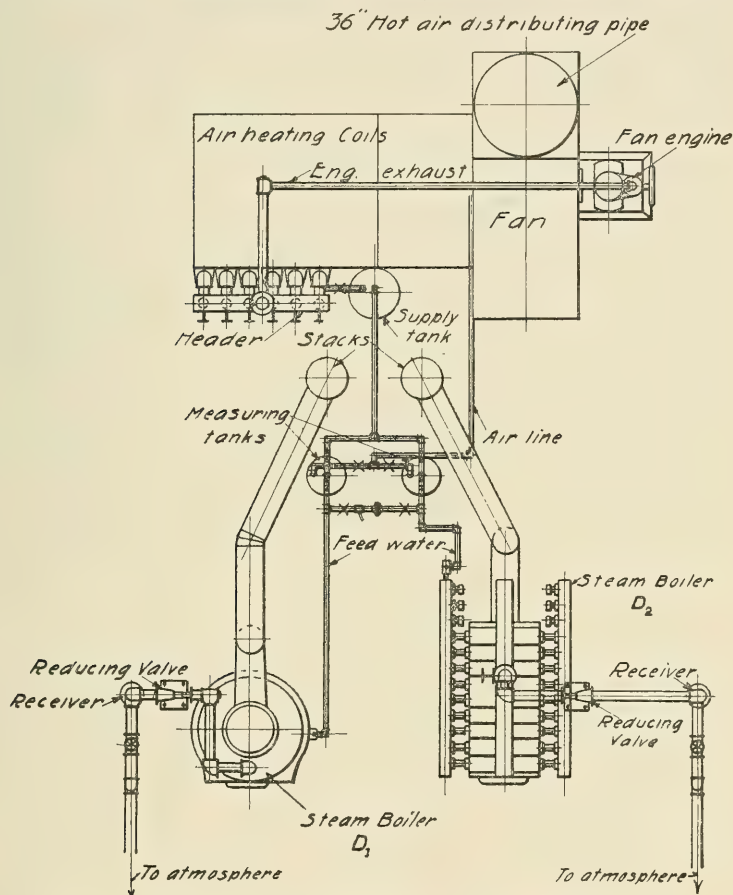


FIG. 10 PLAN OF HOUSE-HEATING BOILER TEST PLANT
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS

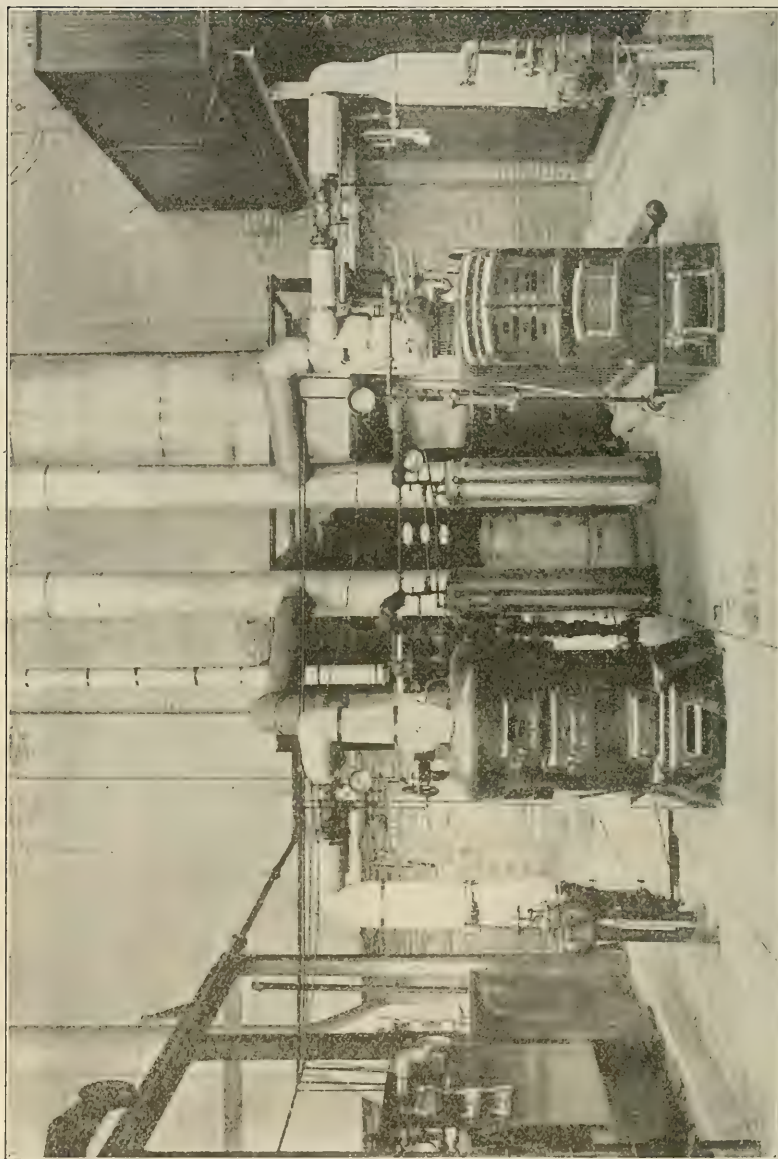


FIG. 11 GENERAL ARRANGEMENT OF PLANT

and boiler D₂. In the U. S. G. S. bulletin, which also reports the principal data and result of these tests, boilers D₁ and D₂ are referred to respectively as boilers A and B.

In Fig. 10 is shown in plan the arrangement of the plant, and in Fig. 11, from a photograph, is shown the general arrangement. The boilers are set independently, each being provided with similar load regulators, return feed water systems, and stacks. The flow is so arranged that the steam may be discharged to the atmosphere through an exhaust head above the roof of the building, or into heating coils at the rear of the boilers. These coils contain 1000 sq. ft. of radiating surface and are arranged in six sections, any number of which may be cut out, changing the amount of radiation in proportion. They form a part of the regular heating system of the laboratory.

Boiler D₁ is made up of four horizontal cast-iron sections, the base and grate section, the fire-pot, an intermediate circulation section, and the dome. Fig. 12 gives a view of the boiler erected. The water space surrounds the fire-pot, and is continued into the intermediate and dome sections through three nipples.

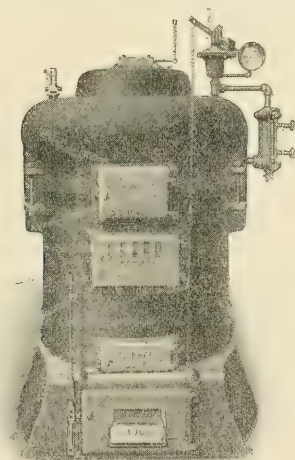


FIG. 12 BOILER D₁

The boiler upon which the tests were made is one rated at 800 sq. ft. The principal dimensions and proportions of this boiler are given in Table 8.

TABLE 8

DIMENSIONS OF BOILER D₁

Rated capacity, radiating surface	square feet	800
Height over all	feet	5½
Floor space	square feet	9
Size of fire door	inches	8½ x 15
Height of fire door above grate	inches	14
Fuel capacity to center of fire door	pounds	290
Kind of grate		plain rocking
Size of grate	inches	28 diameter
Area of grate surface	square feet	4.28
Area of air space	square feet	2.15
Ratio of air space to grate surface	per cent	50
Mean height of furnace	inches	22.5
Height of chimney above grate	feet	39
Sectional area of chimney	square feet	1.07
Area of flue connecting to chimney	square feet	.55
Length of flue connecting to chimney	feet	14
Least flue area in boiler	square feet	.67
Ratio of least flue area to grate surface	per cent	15.5
Smoke outlet above grate	feet	4.17
Kind of draft		natural
Direct water heating surface	square feet	18.8
Indirect water heating surface	square feet	20.7
Superheating surface	square feet	4.2
Total heating surface	square feet	43.7
Ratio of direct heating surface to total	per cent	43
Ratio of total heating surface to grate surface		10.2 to 1
Total water and steam space	cubic feet	7.38
Steam space	cubic feet	3.07
Water space	cubic feet	4.31
Square feet of external boiler surface in contact with water or steam		37.88

Boiler D₂ represents a type of sectional construction in which the base or grate portion and the water-heating portions are built up of interchangeable cast-iron sections, these sections or water legs being connected by means of external circulation drums or headers. Fig. 13 and 14 are respectively an assembled and a sectional view of the boiler, and give an excellent idea of the water space, gas travel, and general construction.

Fig. 13 is from a photograph of the boiler tested.

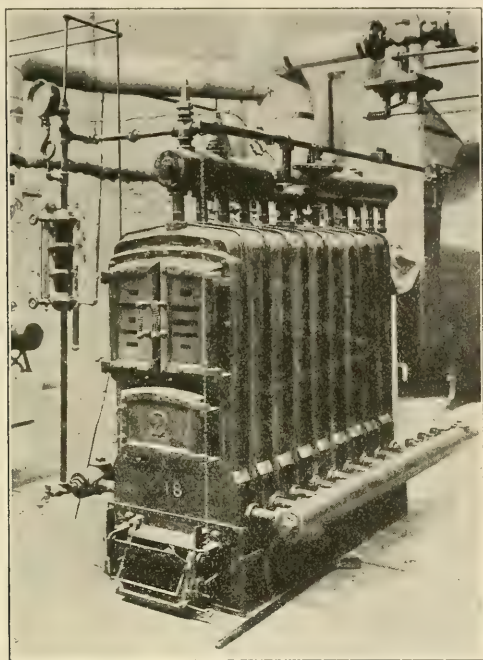


FIG. 13 BOILER D₂

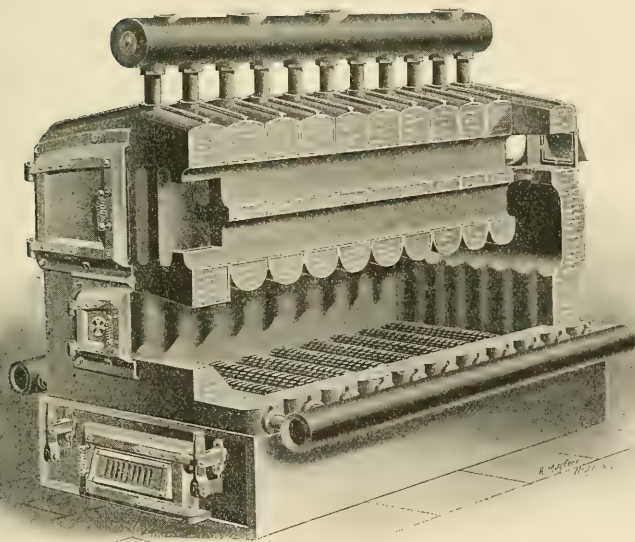


FIG. 14 SECTIONAL VIEW BOILER D₂

This type of boiler is particularly adapted to a number of experimental studies of house-heating boiler work as related to boiler proportions, on account of the ease with which such proportions may be varied. This boiler is manufactured in three widths of grate, and boilers of different capacities are obtained by combining with the different widths of grate a greater or less number of water leg and grate sections.

The boiler installed in the plant has a grate 18 in. wide, is supplied with ten intermediate sections, and with 13-hole supply and return drums, so that a number of combinations are available.

For the tests here considered the boiler consisted of nine sections. The principal dimensions and proportions are given in Table 9.

TABLE 9

DIMENSIONS OF BOILER D₂

Rated capacity, radiating surface.....	square feet	1075
Height over all.....	feet	5 $\frac{3}{4}$
Floor space.....	square feet	25
Size of fire door.....	inches	9 x 15
Height of bottom of fire door above grate	inches	10
Fuel capacity to center of fire door.....	pounds	370
Kind of grate.. . . .		patent rocker
Width of grate	inches	18
Length of grate.....	inches	48
Area of grate surface.....	square feet	6.0
Area of air space... . .	square feet	3.0
Ratios of air space to grate surface....	per cent	50
Mean height of furnace.. .	inches	22
Height of chimney above grate.....	feet	39
Diameter of flue.....	inches	14
Sectional area of chimney.....	square feet	1.07
Area of flue connecting to chimney ...	square feet	.55
Length of flue connecting to chimney..	feet	12 $\frac{1}{2}$
Least flue area in boiler.....	square feet	.495
Ratio of least flue area to grate surface	per cent	8.23
Smoke outlet above grate.....	feet	3.0
Kind of draft		natural
Direct water heating surface.....	square feet	21.89

Indirect water heating surface.....	square feet	53.98
Superheating surface.....		none
Total heating surface	square feet	75.87
Ratio of direct heating surface to total.	per cent	28.9
Ratio of total heating surface to grate surface.....		12.6 to 1
Total water and steam space.....	cubic feet	11.16
Steam space.....	cubic feet	3.28
Water space... ..	cubic feet	7.88
Square feet of external boiler surface in contact with water or steam.....	square feet	103.27

(1) *Feed water system.*—The adoption of the arrangement here described, in which the feed water is forced from the measuring tanks into the boiler by means of compressed air, was influenced to some degree by the desire to use condensation water from the heating coils, noted on page 47. It has, however, proved very satisfactory, requiring little attention, and is convenient, since all of the apparatus is located upon the same level and within easy range for the observer. The arrangement of this apparatus is shown in Fig. 10 and 11, pages 45 and 46. The tanks are ordinary galvanized iron range tanks. One supply tank of fifty-four gallons is connected directly in the return from the heating coils. The inlet pipe passes to the bottom of the tank, and the outlet is at the top so that the tank is at all times filled with hot water.

The measuring tanks, or feed tanks, one for each boiler, 35 gallons capacity, are fitted with gage glasses and scales graduated to read pounds direct, correction being made for varying temperatures. An overflow pipe, with valve, located at the top of the scale, allows filling the tank with a definite charge of water.

These tanks, as stated above, are connected with the laboratory compressed air system, and during feeding are under pressure sufficient to force the water into the boilers. A $\frac{1}{2}$ -in. needle valve near the boiler allows close regulation of the feed. The heating system is under three to five pounds pressure, so that the measuring tanks can be filled by simply opening a valve leading to the supply tank. The measuring tanks can be filled somewhat more rapidly if it is desired, by means of compressed air,

suitable connections being in place. The air pressure and boiler are cut off from the measuring tanks and the overflow opened during charging.

(2). *Load regulator and separator.*—Since these small heating boilers are designed to regulate themselves, under control of their automatic damper regulators, the rate of combustion may be kept fairly regular by keeping the rate of evaporation constant. This has been accomplished by the use of a pressure regulator, by means of which a steady flow of steam is discharged from a constant pressure receiver through a suitable orifice into the atmosphere, provision being made for varying the load to suit the specific demand of the test.

The receivers perform the duty of separators and are thus used to replace the usual steam calorimeter, for which reason the receivers and pipes are heavily lagged with hair felt and pipe covering, one inch of felt being first laid next to the iron and above this a one-inch thickness of magnesia pipe covering. The regulators are shown to the right and left of the boilers in Fig. 11, page 46.

Fig. 15 shows one of the load regulators with its covering removed. The steam from the boiler passes through the pressure regulator *A* into a 3-inch pipe, which extends through the top of the receiver and nearly to the reducing tee at the bottom. Here the direction of steam is changed and entrained moisture separated, the dry steam passing up and out through *F* and to the exhaust main *J*, through an orifice plate in the 2-inch union *G*, the pipe *J* being open to the atmosphere. Difference of pressure as between the receiver and on the exhaust side of the orifice plate as at *J*, is indicated by a mercury manometer at *C* made up with suitable connections. A slight back pressure due to friction usually existed in pipe *J*. No attempt was made to compute the evaporation in this manner. The moisture separated from the steam collects in the 3-inch trap *D*, the amount of which is indicated in pounds and fractions on the gage glass. Some moisture originally in the steam is, doubtless, evaporated in passing the reducing valve, consequently correction of computed results for quality of steam and conversion to equivalent evaporation from and at 212° are made on the basis of the mean pressure maintained in the receiver, which is usually about two pounds.

Variation in load is obtained by the introduction of suitable orifices at *G*. The by-pass valve *E*, allows changes to be made during operation, the orifices taking the place of a gasket in the union.

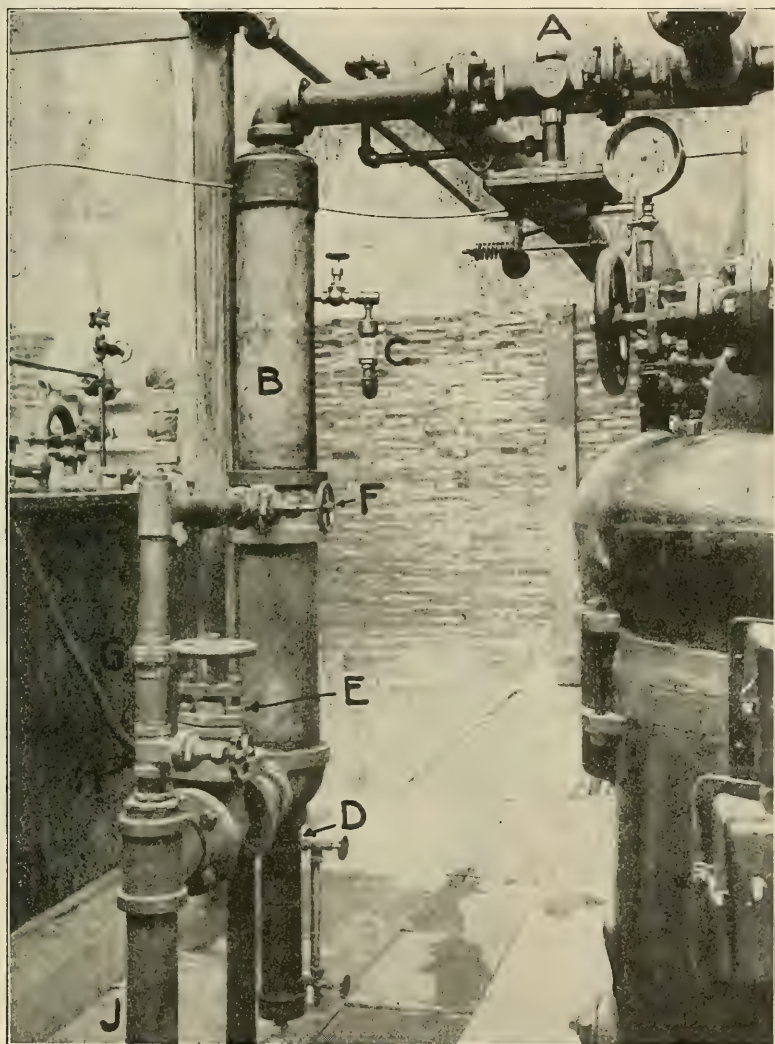


FIG. 15 LOAD REGULATOR

II. FUEL TESTS WITH HOUSE HEATING BOILERS MADE BY THE UNITED STATES GEOLOGICAL SURVEY (58 tests: 47 with briquetted fuel; 11 with raw fuel).

11. *Introduction*

As has been stated already the material presented in Part II was almost entirely supplied through the courtesy of the Technologic Branch of the U. S. G. S. These tests are more fully reported in bulletin No. 366 by the U. S. G. S.

Beginning in October, 1906, a number of evaporative tests were made at St. Louis, Missouri, under the direction of the United States Geological Survey, on the house-heating boiler installed to heat the buildings occupied by the Structural Materials Testing Division. 58 such tests were made; 11 tests were made with raw coal and 47 with briquetted coal having a binder of pitch.

12. *Summary and Conclusions*

The briquets and coal burned on the tests at St. Louis came from eleven states or territories. There were 58 tests, 11 on raw coals, 34 on round briquets and 13 on square briquets. Most tests ran about 8 hours and carried an average steam pressure of from 2 to 3 lb. The amount of fuel fired at each firing varied from 55 to 175 lb. The interval between firings varied considerably; on some tests coal was fired every half hour and on others every two hours. The average efficiency of all of the tests was 51.48; it varied from 38.67 on an Illinois coal to 65.36 on a Virginia coal. The average per cent of builders' rated capacity developed was 59.2. It ranged from 44 per cent on an Illinois coal to 77.2 on an Indian Territory coal. The lowest boiler horse-power developed was 12.1 and the highest 20.6. With fuel at \$1.00 per 2000 lb., the cost of evaporating 1000 lb. of water from and at 212° F. varied from 5.56 cents for a Pennsylvania coal briquetted to 11.93 cents for an Illinois coal briquetted.

Most of the briquets, whether made from eastern or western coal, smoked badly for several minutes after firing. Of the coal tested raw, 6 were on western and 5 on eastern coal. The high volatile western coals smoked badly, but the eastern coals made comparatively little smoke.

13. *Fuel*

Table 10 gives a description of the coal and binders used in the briquets tested. Further information relative to the coal tested and to the binders employed has been published in the bulletins of the U. S. G. S.* The chemical properties of these fuels as shown by proximate and ultimate analyses are contained in Table 16, on page 94, Appendix B.

On comparing the results of tests on the coal and briquets there seems to be no advantage in the briquets over coal of a suitable size for house boiler heating. Briquetting a good bituminous coal would be justified when slack is used for material and the gain would be due almost entirely to the more favorable size of the fuel. This gain is less for coals which coke readily than for non-coking coals which are not suitable for domestic purposes in the form of slack. Briquets made from such coal burn fairly well, as they allow the air to pass up through the fuel bed.

These experiments have shown that the pitch binders used are not suitable for a furnace working at the low temperatures common in a house-heating boiler, as they volatilized and in most cases escaped unburned or were deposited on the surface of the boiler. This coating generally burned off once or twice a day, causing a high temperature in the flue, and, as a consequence, danger from fire.

14. *Methods of Conducting Tests*

The tests were made to conform as nearly as possible to actual running conditions of the average house-heating boiler plant. Steam was supplied to two buildings for heating and consequently the load varied with the weather, according to both the temperature of the outside air and velocity of the wind. On only a few of the tests was the heating load so light that steam was turned into the atmosphere.

The tests usually covered a period of about eight hours; during this time the operator tried to maintain a steam pressure of about three pounds. The alternate method, as prescribed by the A. S. M. E. code for making boiler trials, was used in starting and stopping the tests. The boiler was installed in so small a

* Bulletin 332, Report U. S. Fuel Testing Plant 1906-7.

Bulletin 261, Preliminary Report on Coal Testing Plant.

Bulletin 343, Binders for coal briquets.

TABLE 10 COAL AND BINDERS USED IN BRIQUETS

Coal			Shape of Briquet	Binder <i>a</i>			
Field Designation	Locality	County		Percentage Used	Flowing Point	Oils by Distillation up to 743° F.	Extraction analysis: Pitch extracted (samples received) by CS ₂
Arkansas No. 13.....	Denning.....	Franklin.....	Round..	7	° F. 140.0	Per ct. 34.44	Per cent 95.20
Illinois:							
No. 7 E.....	Near Collinsville.....	Madison.....	" ..	8	143.6	25.76	96.90
No. 9 C.....	Near Staunton.....	Macoupin.....	" ..	9	143.6	25.76	96.90
No. 12 B W.....	Bush.....	Williamson.....	Square..	6.25	143.6	39.05	99.66
No. 29 A W.....	Livingston.....	Madison.....	Round..	7	143.6	39.05	99.66
No. 29 B.....	" ..	" ..	" ..	7	143.6	39.05	99.66
No. 30 W.....	Shiloh.....	St. Clair.....	" ..	8.5	143.6	25.76	96.90
No. 31.....	Warden.....	" ..	" ..	8	143.6	25.76	96.90
No. 31.....	" ..	" ..	Square..	7	161.6	28.98	89.31
No. 33.....	Trenton.....	Clinton.....	Round..	8	143.6	25.76	96.90
Indiana:							
No. 1 B.....	Mildred.....	Sullivan.....	" ..	8.5	161.6	28.98	89.31
No. 5 B.....	Hymera.....	" ..	" ..	9	143.6	25.76	96.90
No. 6 B.....	" ..	" ..	" ..	8.5	143.6	25.76	96.90
No. 6 B.....	" ..	" ..	Square..	7	143.6	25.76	96.90
Indian Territory:							
No. 2 B.....	Hartshorne.....	" ..	Round..	8	186.8	24.70	85.57
No. 2 B.....	" ..	" ..	Square..	8	172.4	20.00	99.60
Kansas:							
No. 2 B.....	Yale.....	Crawford.....	Round..	7	143.6	39.05	99.66
No. 2 B.....	" ..	" ..	Square..	7	143.6	39.05	99.66
Maryland No. 2.....	Frostburg.....	Allegheny.....	Round..	8	143.6	25.76	96.90
Missouri No. 10.....	Bevier.....	Macon.....	" ..	8	143.6	39.05	99.66
Pennsylvania:							
No. 18.....	Lloydell.....	Cambria.....	" ..	8	143.6	25.76	96.90
No. 18.....	" ..	" ..	Square..	7	143.6	25.76	96.90
No. 18.....	" ..	" ..	" ..	68	114.8	5.76	100.00
No. 19.....	Herminie.....	Westmoreland.....	Round..	8	143.6	25.76	96.90
No. 20.....	Near Seward.....	" ..	Square..	6	161.6	28.98	89.31
No. 20 W.....	" ..	" ..	Round..	8	161.6	28.98	89.31
No. 22.....	Huff.....	" ..	" ..	7	161.6	28.98	89.31
No. 22.....	" ..	" ..	Square..	6	161.6	28.98	89.31
Pennsylvania No. 15 (one-fourth).	Wehrum.....	Indiana.....	Round..	6.25	143.6	39.05	99.66
Rhode Island No. 1 (three-fourths).	Cranston.....	Providence.....	" ..	" ..	" ..	" ..	" ..
Pennsylvania No. 18 (one-fourth).	Lloydell.....	Cambria.....	" ..	8	143.6	25.76	96.90
Miscellaneous No. 9 (three-fourths).	" ..	" ..	" ..	" ..	" ..	" ..	" ..
Pennsylvania No. 18 (one-half).	Lloydell.....	Cambria.....	" ..	8	156.2	25.47	90.56
Rhode Island No. 1 (one-half).	Cranston.....	Providence.....	" ..	" ..	" ..	" ..	" ..
Pennsylvania No. 18 (three-fourths).	Lloydell.....	Cambria.....	" ..	8	143.6	25.76	96.90
Miscellaneous No. 9 (one-fourth).	" ..	" ..	" ..	" ..	" ..	" ..	" ..
Pennsylvania No. 18 (one-half).	Lloydell.....	Cambria.....	" ..	8	143.6	25.76	96.90
Miscellaneous No. 9 (one-half).	" ..	" ..	" ..	" ..	" ..	" ..	" ..
Virginia No. 5 B.....	10 miles west of Blacksburg	Montgomery.	" ..	7	143.6	39.05	99.66

a Water-gas pitch except where otherwise noted.*b* Wax tailings.

room that the standard method of starting and stopping the tests was not practicable.

Each test was started with a fire about 4 in. thick. This thickness was gradually increased, varying from 12 to 18 in. depending upon the kind of coal burned and upon the judgment of the operator as to the best thickness for good combustion. To start a test with a 4-in. fuel bed required that the same coal used on the test must be fired for about four hours before the start of the test. To build up the fire required light firings at first and the same procedure was followed to burn it down for a close. At other times during the tests the amount of coal fired was considerably greater. Coal was fired whenever the heat requirements demanded it, usually at a time when the fire had burned down and the steam pressure had dropped. When the coal was fired it was spread over the entire fuel bed. The fire seldom required any attention and it was never poked unless a coal was being burned that coked badly. On the tests the fire was cleaned only just before starting and stopping, except in two or three cases when there was an unusually large accumulation of clinker upon the grate.

Readings were taken of draft, temperature and steam pressure, every 30 minutes. Smoke readings were taken as soon after coal was fired as other observations would permit and it was observed at intervals until the volatile matter had been driven off and no smoke was given off from the stack.

Owing to the many duties of the observer there was difficulty in securing and analyzing representative samples of flue gas, but the results are considered of sufficient accuracy to indicate certain general relations between the air supply and the performance of the boiler.

All gas samples analyzed gave some CO in the flue gas. This was to be expected as the combustion was never complete on any of the tests as evidenced by watching the top of the stack.

Observations showed the smoke black at times of firing and comparable with the Ringelmann charts, gradually turning gray after several minutes. This is of interest owing to the fact that the gases resulting from the combustion of briquets at the Illinois Engineering Experiment Station were usually of a dirty yellowish color and not comparable with the usual standard.

All briquets were fired whole. Shortly after they were fired

distillation of the tar took place and condensed on the boiler surface, forming a covering over the flue passages. When the fire was allowed to burn freely the coating on flues ignited. This often happened two or three times during an eight hour run and would increase the temperature in the flues as high as 1500°F . On this account a thermo-couple was used to take the temperature of the stack gases.

The furnace door was opened only at times of firing. An attempt was made on a few special briquet tests to reduce the smoke after firings by opening the slide draft in the furnace door, but either there was not enough air or it was admitted at the wrong point for there was no appreciable reduction of smoke. No attempt was ever made to introduce air over the fire on the regular series of tests.

The flue passages were not brushed during the tests with briquets as the burning of the tar effectually cleaned the boiler surfaces. In some cases the tar coating without doubt greatly lowered the efficiency of the boiler. It will be noted that the raw coal gave better results than when briquetted.

The analyses of the fuel burned and of the refuse were made at the chemical laboratory of the fuel testing plant.

15. *Data and Results*

In Table 16, pages 92 to 98, Appendix B, will be found the principal data and results relative to these tests. Table 17, page 99, gives the average per cent of CO_2 , O_2 and CO for 52 of the tests.

16. *Equipment*

Fig. 16 and 17, pages 59 and 60 show plan and elevation drawings of the house-heating boiler plant as tested at St. Louis.

The boiler on which these tests were made is of the sectional type. It contains seven separate sections, measures 66 in. in length, has a grate $36 \times 54\frac{1}{2}$ in., three 5-in. steam outlets at the top of the sections and is rated to take care of 3150 sq. ft. of radiating surface.

The boiler furnished steam to two buildings, supplying the necessary amount through two of the three outlets. The front outlet was not in use and was capped over. This boiler is made so that feed water may be supplied to every other section. It enters at the base of the section on both sides just above the grate level. There are six return inlets, but in this installation

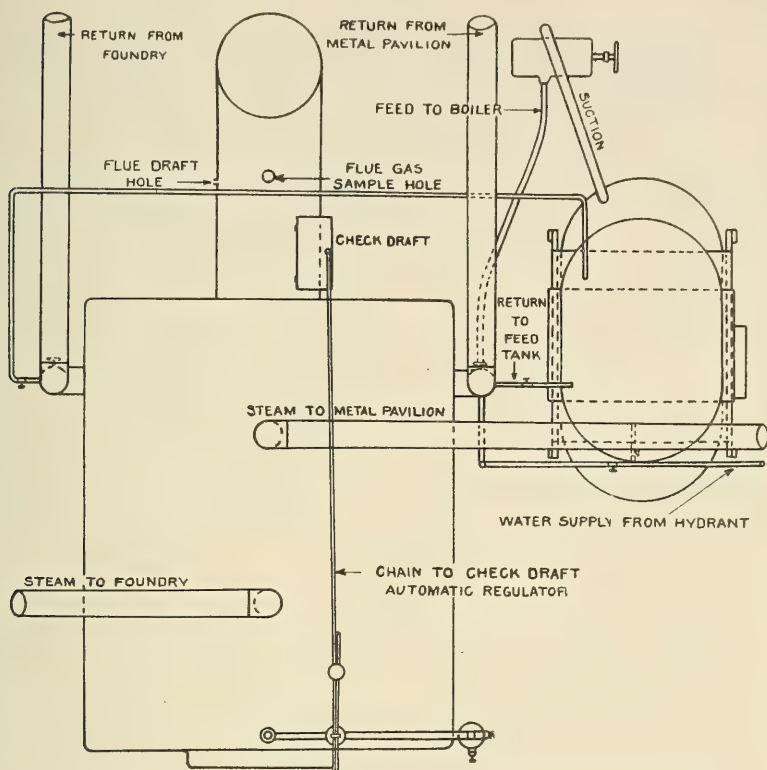


FIG. 16 PLAN OF HOUSE-HEATING BOILER PLANT AT
ST. LOUIS, MO.

only the rear two were used. The piping was so arranged that during a test period all of the condensation was returned to a weighing tank, then allowed to discharge into a supply tank from which it was forced into the boiler by means of a hand pump. The temperature of the water entering the boiler varied from 100° to 150° F., but usually averaged 140° F. During a test all the water entered the boiler through one of the rear inlet openings.

A sectional boiler is usually installed so that the steam as it is taken from the sections is first drawn into a collecting drum, so that water will not be carried into the pipes with the steam in case of a sudden demand for steam. There was not enough head room for the installation of this drum at the St. Louis plant and the steam was drawn directly from two sections. Drain pipes con-

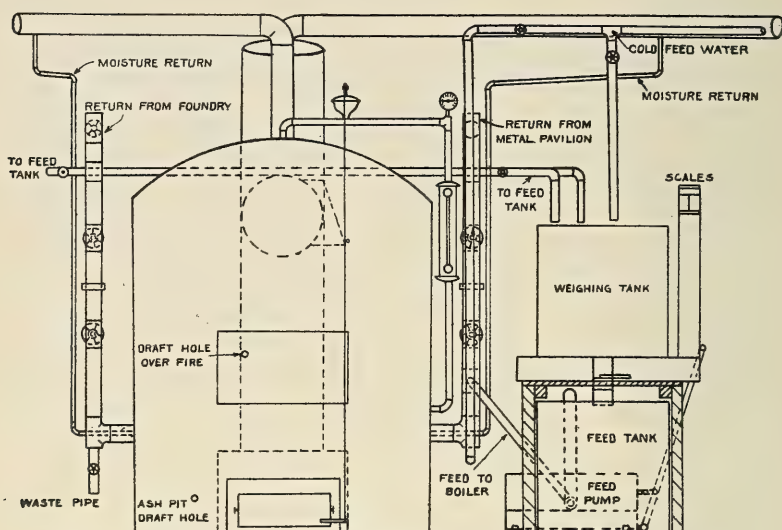


FIG. 17 ELEVATION OF HOUSE-HEATING BOILER PLANT AT
ST. LOUIS, MO.

connected with the bottom of the steam pipes, as shown in the drawing, carried moisture back to the boiler. No moisture readings were made on the steam; therefore, in making calculations on the amount of water evaporated, the moisture was not accounted for and the boiler has been credited with slightly more work than it performed.

A siphon damper regulator was used to control the draft through the fire so that a nearly constant steam pressure might be carried. This regulator was connected direct to the lower check also by an arrangement of pulleys to the check in the flue.

On the first 30 tests the draft was supplied by a stack 32.4 ft. above the grate. On these tests both natural and induced draft were used. On the last 28 tests the stack was raised to 44.8 ft. above the grate level. This height of stack always furnished the required amount of draft.

All except the front of the boiler was lagged with about an inch covering of plastic asbestos.

III. FUEL TESTS WITH HOUSE-HEATING BOILERS MADE BY THE ENGINEERING EXPERIMENT STATION (24 tests with briquetted fuel)

17. *Introduction*

24 tests were made when burning briquetted fuel in connection with house-heating boilers by the Engineering Experiment Station of the University of Illinois during the months of June and July, 1907. The tests described in Part II of this article made by the U. S. G. S., at St. Louis, led to the desire to conduct additional tests under more constant conditions than could be maintained at the St. Louis plant.

18. *Summary*

An average capacity of 65 per cent was carried on all of the 24 tests, the variation being from 53.2 to 71.4 per cent. The boiler horse-power developed on boiler D₁ ranged from 4.52 to 4.96; on boiler D₂ from 4.97 to 6.16. The average efficiency of the boiler and furnace, figured on a dry coal basis, gave 44.85 per cent for the 24 tests. Comparing 8 tests on briquets, 4 of which were made on large briquets and 4 on small briquets, it is shown that in every case the large briquets gave an appreciably higher efficiency showing that the size of the coal burned is an important factor. With fuel at \$1.00 per 2000 lb., the cost of evaporating 1000 lb. of water from and at 212° F., varied from 6.74 cents on a Pennsylvania briquet test to 12.47 cents on an Illinois test.

The briquets started readily from a wood fire and burned well, but owing to the difficulty of obtaining complete combustion, the average efficiency from an 8 hour test was low. The formation of soot in the flues of boiler D₂ was more troublesome than in boiler D₁. In two instances the flues of boiler D₂ were completely stopped up after an 8-hour run.

To carry only 65 per cent of the rated radiating surface the draft through the fire was either cut off or very nearly so for one-half to three-quarters of the time.

19. *Fuel*

A carload of briquets was shipped to the Engineering Experiment Station at Urbana, Illinois, and the results here recorded are from tests made with this fuel. The briquets were manufactured at the U. S. G. S. fuel testing plant and were of two sizes and shapes. The round briquets were $3\frac{1}{8}$ in. in diameter and 2 in. thick. The square briquets were $4\frac{1}{4}$ in. x $6\frac{3}{4}$ in. x $2\frac{1}{2}$ in. 24 tests were made, twelve on each of two boilers. 18 of the tests were on round briquets manufactured with the Renfrow briquetting machine, the other six with square briquets made on the English briquetting machine. These machines and their products have been described in the bulletins issued by the U. S. G. S., concerning the fuel testing plant at St. Louis.* The square briquets were broken in halves before firing. The percentages of pitch in the briquets varied from 7 per cent to 8 per cent. The chemical properties of these fuels as to moisture and ash are given in Table 18, page 104, Appendix C.

20. *Methods of Conducting Tests*

The methods employed in conducting the tests were also in general the same as those used in making the tests considered in Part I and have been described in connection with those tests under the heading "Methods of Conducting Tests" upon pages 15 to 20 inclusive. For the tests here considered the following are the principal conditions under which they were planned to be run.

(1). The load to be maintained between 60 and 70 per cent of the builders' rated capacity.

(2). The load to be uniform throughout the test.

(3). A steam pressure of 2 lb. to be carried on the heating system.

(4). A definite charge of coal to be supplied at each firing.

(5). Each test to be of approximately 8 hours' duration.

The air supply was taken entirely through the ash-pit door. On some of the tests it might have been advisable to continuously admit a part of the air used for combustion over the fire through the furnace door or it might have been possible to have increased the over-all efficiency of the boiler by admitting air

*Professional Paper No. 48, Part III.

Bulletin 261. Preliminary Report on Coal Testing Plant.

Bulletin 290. Operations of Fuel Testing Plant in 1905.

Bulletin 332. Report U. S. Fuel Testing Plant, 1906-7.

Bulletin 343. Binders for Coal Briquets.

over the fire for a few minutes after each firing by cracking the furnace door; however, since this is not commercially practicable, no attempt was made to prove or disprove the statement.

The boiler flues were blown after the close of every test, so that the heat developed on each of the tests had an equal chance on the heating surface at the start of the test; however, on some of the trials more soot was formed than on others, which made the heating surface on these trials much less effective at the close of the test than at the start.

The standard method of the A. S. M. E. code for conducting boiler trials was employed, the test being started when the wood was lighted. As soon as the wood was burning well, about 25 lb. of the fuel was fired. In about 8 or 10 minutes, the remainder of a 75-lb. charge of fuel was fired.

Observations concerning temperatures, pressures, drafts and water measurements were recorded every 15 minutes.

As the duration of the trials was to be approximately 8 hours, just enough coal was put on the fire at the last firing to keep up 5 pounds steam pressure until time to close the test.

21. *Data and Results*

In Table 18, pages 102 to 108, Appendix C, will be found the principal data and results relative to these tests.

(1). *Soot*—Table 11, below, shows the amount and character of soot found on flues of boilers D₁ and D₂ as determined and recorded at the end of test. Measurements were taken in the flues of the boiler.

TABLE 11
AMOUNT AND CHARACTER OF SOOT FORMED IN FLUES

Test No.	Boiler	Soot Measurements	Test No.	Boiler	Soot Measurements
136	D1		140	D1	Heavy; $\frac{1}{8}$ inch thick
137	D2		141	D2	Heavy; $\frac{1}{8}$ inch to $\frac{1}{4}$ inch thick.
152	D1	Heavy; 1-16 inch to $\frac{1}{8}$ inch thick	146	D1	Heavy; large amount.
153	D2	Heavy; 1-16 inch to $\frac{1}{8}$ inch thick.	147	D2	Large amount; choked draft entirely off.
154	D1	Light and fluffy; $\frac{1}{8}$ inch thick.	148	D1	1-16 inch to $\frac{1}{8}$ inch thick.
155	D2	Light and fluffy; $\frac{1}{8}$ inch thick. Choked draft entirely off.	149	D2	Heavy; large amount.
142	D1	Heavy.	138	D1	Very little.
143	D2	Heavy.	139	D2	Very little.
144	D1	Heavy.	156	D1	Fine and heavy; small amount.
145	D2	Heavy.	157	D2	Very little.
158	D1	Very little.	150	D1	1-16 inch thick or less.
159	D2	Flaky; $\frac{1}{4}$ inch thick.	151	D2	1-16 inch thick or less.

Owing to the fact that the character of the soot was so variable, it is difficult to draw any conclusion on comparative thickness of soot. The above table shows that there was a big variation in the amount of soot formed. It is noticeable that on several of the tests a great deal of soot lodged in the flues and in a few instances the flues were filled, choking the draft off entirely. More difficulty was experienced with soot on Boiler D₂ than on D₁.

(2). *Smoke*—The smoke observations for the tests made at the Illinois Engineering Experiment Station are not reported owing to the uncertainty of comparative accuracy. The readings were extremely difficult to estimate, due largely to the peculiar color of the smoke. Smoke of about a shade between Ringelmann No. 1 and No. 2, from briquets made with pitch binder, is of a dirty yellowish color and far more offensive than No. 4 smoke from raw or washed coal, and probably would be of about the same gravimetric density as the No. 4 smoke from coal. On all briquet tests, the stack smoked badly for three-quarters of an hour after firing. After about one hour after firing the stack was almost clean, remaining so until another charge was fired.

22. *Equipment*

The equipment used in making these tests consisted of the two house-heating boilers installed by the Engineering Experiment Station of the University of Illinois and designated as boiler D₁ and boiler D₂. Except for a few minor changes in regard to the type or arrangement of the apparatus used in making observations, the equipment and its arrangement are the same as employed when making the 48 tests considered in Part I of this bulletin. Description of this equipment has already been given and will be found upon pages 45 to 53, inclusive.

APPENDIX A

APPENDIX A

23. *Tabulated Results*

The principal data and calculated results of the 48 tests are given in Table 12, on pages 70 to 83. The column heading numbers ranging from 1 upon page 70 to 73 upon page 82, correspond to the item numbers upon a final report sheet which was worked up for each test, and in general are arranged in much the same order as corresponding items in the A. S. M. E. code for boiler trials.

The first three columns upon each page of Table 12 are the same, and serve as a guide in showing the connection throughout the different pages. These columns give the laboratory test number, the boiler operated and the kind of fuel used.

Upon page 70 are given the date upon which the test was made, the length of the test in hours, and average values of steam pressures, drafts and temperatures. The average steam pressures are in no case recorded closer than to the nearest half pound. The manometer on the receiver, being connected to give the difference in pressure between the two sides of the orifice, did not indicate the true pressure in the receiver. The pressure on the exhaust side of the orifice plate was, however, so small as not to make the average pressure higher than 2 lb. as recorded above. It will be noted that in one test the average pressure in the receiver was 1.5 lb.

The draft in the ashpit was taken along with other observations at regular 20 minute intervals. Owing to the fact that at the time of taking such observations the damper to the ash-pit might be in any position from tightly closed to wide open, an average of such readings would be of little or no value and has been omitted from the tabulated results. In general the draft in the ash-pit varied from practically zero when the ash door opening was wide open, to approximately the same draft as existed over the fire when the damper was closed. A record of the position of the ash door damper and the smoke pipe check was kept in connection with the observations made upon drafts.

Pages 72 and 75 contain information relative to the fuel. Items 20, 21 and 21.1 show the amount of moist fuel fired while item 21.2 shows the same as corrected on account of the residual fuel drawn at the end of the test. Items 23 and 23.1 show the amount of fuel expressed as dry or moisture-free fuel. Item 23.2 gives the amount of dry fuel actually consumed, further correction having been made allowing for the unburned fuel removed with the ash. Items 24 and 25 exhibit respectively the ash and residual fuel which were obtained for each test. Items 37 and 38, page 76 give the analyses of the residual fuel as divided into carbon and earthy matter, while items 40 and 41 give corresponding information relative to the ash. Items 45 and 46 give the calorific value for the fuel used in each test expressed upon both a dry fuel and upon a fuel as fired basis. Items 43 and 44 exhibit the average rate of combustion maintained, expressed as dry fuel per hour and as dry fuel per square foot of grate surface per hour.

Upon page 74 are given the proximate analyses of the fuel for each test with the items expressed in per cent of fuel as fired and moisture-free coal. This table has already been referred to in the sections concerning fuel and methods.

Page 78 presents information relative to the water evaporated. Item 47 gives the moisture in the steam as determined in the receiver. The steam from the boiler to the receiver was probably dried to a considerable extent in passing the reducing valve and a part of the moisture collected in the receiver is due to condensation rather than entrained moisture. The moisture as here recorded is not a measure of the dryness of the steam as generated by the boiler at boiler pressure. It has, however, been used in the calculations for determining boiler performance as the moisture in the steam when reduced to receiver pressure. It will be noted that the moisture content so determined is comparatively small and the corresponding corrections of little effect in the final determinations regarding evaporative performance. Items 49, 50 and 52 give the amount of water fed to the boiler, the same corrected for quality of steam to give the amount evaporated and the equivalent evaporation from and at 212° F. Items 53 and 54 give operating conditions with reference to water evaporated, showing the total equivalent evaporation per hour and the same per square foot of heating-surface per hour. Items 48 and 51 are factors used in calculating other items listed on the table.

Upon page 80 are given results relative to the load carried. As already stated, the attempt was made to run at a load equal to approximately 65 per cent of the boiler rating. An examination of the per cent given under item 56 shows that the highest capacity recorded for any test was 71.25 per cent and the lowest 58.33 per cent, the remainder of the values ranging between these two. Item 55 gives the load expressed in square feet of radiation served. For the purpose of calculating this load an evaporation of 0.3 lb. of water from and at 212° F. was considered equivalent to serving one square foot of radiation for one hour. Table 8 shows that of the external boiler surface of boiler D₁, 37.88 sq. ft. was on the inner side in contact with steam and water, and Table 9 shows that 103 27 sq. ft. of the surface of boiler D₂ was under similar conditions. This surface could be considered radiating surface and if added to the surface served as shown by item 55 would increase the load and show the boiler operating at a somewhat higher capacity than is shown by item 56, which is based upon evaporation only, without regard to radiation loss from the boiler. Item 55.1 shows the load carried when this boiler radiating surface is added to the load as calculated from evaporative performance. It is inserted here in order to call attention to the very considerable difference which such an assumption would make, but is not otherwise used in any of the calculations involving capacity, item 55 being used for that purpose. It was not considered advisable to make use of item 55.1 owing to the uncertainty as to how closely a square foot of the boiler radiating surface might be considered equivalent to a square foot of radiation as defined above, and especially on account of the fact that house-heating boilers in service may not be lagged and their exposed surface is rarely considered in estimating the radiating surface served. In case the boilers under consideration were lagged a portion only of the heat lost by radiation could have been utilized in evaporating water.

Items 57 and 58 give the equivalent evaporation per pound of fuel. Items 59 and 60 give the fuel consumed per hour per 100 sq. ft. of radiation, expressed in fuel as fired and in dry fuel.

Items 61 and 62, page 82, give efficiencies as calculated in the usual manner. Item 61 gives the efficiency when only the boiler and furnace are considered. Item 62 gives the plant efficiency,

that is, the efficiency of the boiler, furnace and grate. The same grates were used throughout and the efficiency of boiler and furnace without grate differs from the efficiency with grate only on account of the unconsumed fuel which passed through the grate. The grates may have been more suitable for the retention of some of the fuels than of others. In so far as the grate serves as a part of the furnace, as in the matter of air supply, its effect is of course included in both efficiencies.

Items 64 and 65 give the cost of serving 100 sq. ft. of radiation and of evaporating 1000 lb. of water from and at 212° F. based upon an assumed fuel cost of \$1.00 per ton of 2000 lb.

Items 70, 71, 72 and 73 give a number of the conditions which prevailed with respect to fire conditions. Item 70 (fuel fired at each firing) shows that 75 and 105 lb. of fuel constituted the firing charge for boilers D₁ and D₂, respectively. The first fire of each test, however, consisted of this amount of fuel and a sufficient weight of white pine kindling to ignite it. From 15 to 25 lb. of kindling were used in this manner upon each test. In all calculations involving fuel this kindling was allowed for on the basis of 1 lb. of wood being equivalent to 0.4 lb. of the fuel employed.

In calculating item 72 (average interval between times in shaking and raking) each firing was considered as a time of shaking and raking, whether the fire was touched or not, other than to put on fresh fuel, also poking, leveling, or other working of the fire was so considered. Where the average interval between times of shaking and raking is the same as the average interval between firings (item 71) the fire was not touched between firings throughout the test.

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA¹

Test Number	Boiler	Kind of Fuel	Date 1908	Duration of Test (hours)	Average Pressures			Average Temperatures (°F)			
					Boiler	Receiver	Draft (in. of water)	Boiler Room	Feed Water	Flue Gas	
				1	10	11	12	13	15	16	17
162	D1	Anthracite	February 24	8.77	5.0	2.0	.13	.10	83	171	585
166	.....	.....	March 2	16.55	4.5	2.0	.15	.11	85	171	435
168	.....	.....	May 4 & 5	23.15	4.0	2.0	.21	.12	76	178	604
163	D2	Anthracite	February 24	18.00	5.0	2.0	.08	.05	82	174	536
167	.....	.....	March 2	17.52	6.0	2.0	.08	.05	85	173	528
187	.....	.....	May 4 & 5	96.00	5.5	2.0	.12	.07	76	178	500
172	D1	Pocahontas	March 17	10.07	5.0	2.0	.17	.12	84	164	389
174	.....	.....	March 21	17.03	3.5	1.5	.16	.13	83	170	613
176	.....	.....	March 23 & 24	95.13	4.0	2.0	.18	.13	80	175	594
173	D2	Pocahontas	March 11	12.65	5.5	2.0	.12	.09	83	156	482
175	.....	.....	March 21	16.05	5.5	2.0	.13	.07	83	171	554
177	.....	.....	March 23 & 24	25.93	5.5	2.0	.13	.08	80	173	525
178	D1	Gas House Coke	April 11	8.43	5.5	2.0	.13	.11	92	166	560
199	.....	.....	May 21	9.57	4.0	2.0	.13	.11	80	177	528
180	.....	.....	April 7	15.83	4.0	2.0	.12	.10	80	175	568
213	.....	.....	June 18	17.15	5.0	2.0	.30	.09	94	170	410
201	.....	.....	May 22 & 23	23.70	3.5	2.0	.17	.14	80	172	536
182	.....	.....	April 17 & 18	26.23	3.5	2.0	.10	.09	79	175	605
179	D2	Gas House Coke	April 6	11.70	6.0	2.0	.12	.07	83	174	499
200	.....	.....	May 21	11.85	5.5	2.0	.09	.05	91	175	479
181	.....	.....	April 7	14.92	6.0	2.0	.12	.07	80	173	497
185	.....	.....	May 2	15.55	5.5	2.0	.10	.06	72	146	472
183	.....	.....	April 17 & 18	24.85	6.0	2.0	.11	.07	80	173	421
202	.....	.....	May 22 & 23	54.17	6.0	2.0	.10	.06	80	175	481
197	D1	Solway Coke	May 19	10.63	4.0	2.0	.14	.11	88	178	511
195	.....	.....	May 18	15.17	4.0	2.0	.13	.11	86	178	513
192	.....	.....	May 11 & 12	26.53	3.5	2.0	.15	.12	82	179	504

207	D ²	Solway Coke.....	June 5.....	12.58	5.5	2.0	.06	.04	57	177	451
196	....	....	May 18.....	16.32	6.0	2.0	.09	.06	86	177	429
193	....	....	May 11 & 12.....	25.55	5.5	2.0	.08	.06	82	182	409
215	D ¹	Illinois, Williamson county.....	June 22.....	8.63	4.5	2.0	.33	.04	102	182	412
211	....	....	June 16.....	17.68	5.0	2.0	.29	.06	83	186	436
217	....	....	June 25 & 26.....	23.48	5.0	2.0	.45	.02	81	173	617
214	D ²	Illinois, Williamson county.....	June 18.....	9.88	5.5	2.0	.07	.03	95	182	521
212	....	....	June 16.....	15.58	5.5	2.0	.09	.05	84	172	471
218	....	....	June 25 & 26.....	23.18	5.5	2.0	.19	.07	84	175	587
238	D ¹	Illinois, Macon county.....	July 27.....	9.78	5.0	2.0	.35	.05	37	176	523
231	....	....	July 24.....	16.73	5.0	2.0	.25	.07	94	177	545
232	....	....	July 22 & 23.....	24.58	5.0	2.0	.88	.07	91	179	483
237	D ²	Illinois, Macon county.....	July 27.....	8.38	5.5	2.0	.13	.05	98	179	574
235	....	....	July 24.....	16.03	5.0	2.0	.16	.06	94	183	556
233	....	....	July 22 & 23.....	23.13	5.5	2.0	.13	.04	92	183	550
241	D ¹	Illinois, Vermilion county.....	July 31.....	7.97	4.5	2.0	.38	.03	97	169	544
243	....	....	August 3.....	16.45	5.0	2.0	.40	.06	97	170	535
239	....	....	July 29 & 30.....	24.47	4.5	2.0	.22	.05	94	175	560
242	D ²	Illinois, Vermilion county.....	July 31.....	8.55	6.0	2.0	.18	.06	97	177	615
244	....	....	August 3.....	15.07	5.5	2.0	.17	.05	98	183	613
240	....	....	July 29 & 30.....	25.02	5.5	2.0	.16	.06	93	179	583

1See "7. Tabulated Data and Results," p. 20.

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(Continued)

Test Number	Boiler	Kind of Fuel	Fuel as Fired (pounds)				Dry Fuel (pounds)			Total Ash and Refuse From Ash Pit (pounds)	Residual Fuel Removed (pounds)
			Wood	Coal	Coal Plus Wood	Corrected For Residual Fuel	Total Fired	Corrected For Residual Fuel	Actually Consumed (Corrected For Ash)		
			20	21	21.1	21.2	23	23.1	23.2	24	25
162	D1	Anthracite	25	275	285	221	274	213	207	11.25	78.50
166	D1	Anthracite	25	450	460	391	443	376	365	24.75	90.50
186	D2	Anthracite	25	600	610	533	585	511	495	40.25	102.75
163	D2	Anthracite	30	315	327	225	314	216	206	14.75	115.25
167	D1	Pocahontas	30	525	537	452	517	485	414	39.00	103.50
187	D1	Pocahontas	30	735	747	637	716	610	587	47.00	146.50
172	D1	Pocahontas	15	225	231	217	226	213	204	14.00	21.00
174	D1	Pocahontas	15	375	381	369	373	361	352	17.75	24.00
176	D2	Pocahontas	15	600	606	595	594	584	564	36.25	39.00
173	D2	Pocahontas	20	315	323	303	317	297	277	28.25	32.00
175	D1	Gas House Coke	20	420	428	406	419	398	378	31.50	33.00
177	D1	Gas House Coke	20	630	638	621	625	608	581	44.50	26.75
178	D1	Gas House Coke	20	225	233	217	216	204	201	6.50	28.25
199	D1	Gas House Coke	20	225	233	216	216	201	197	11.50	27.00
180	D1	Gas House Coke	20	375	383	366	365	349	347	10.00	37.50
213	D1	Gas House Coke	20	375	383	366	365	347	344	14.50	35.75
201	D1	Gas House Coke	20	525	533	516	501	485	479	31.00	36.25
182	D2	Gas House Coke	20	600	608	580	567	541	538	26.50	42.75
179	D2	Gas House Coke	25	315	325	296	301	275	270	11.75	40.50
200	D2	Gas House Coke	25	315	325	296	301	275	268	17.75	40.00
181	D1	Gas House Coke	25	420	430	396	410	378	373	15.50	52.00
185	D1	Gas House Coke	25	420	430	401	414	386	382	10.90	53.00
183	D1	Gas House Coke	25	630	640	603	597	563	559	28.00	53.00
202	D1	Gas House Coke	25	630	640	613	602	577	569	38.25	49.50
197	D1	Solvay Coke	20	225	233	216	228	212	208	9.75	26.50
185	D1	Solvay Coke	20	300	308	291	302	285	284	10.00	32.00
192	D1	Solvay Coke	20	525	533	515	526	508	506	24.50	41.50

207	D2	Solvay Coke.....	25	315	385	302	321	298	298	14.30	37.26
196	...	.....	25	420	430	404	422	386	420	26.00	42.50
193	...	.....	25	630	640	610	631	601	590	29.50	58.25
215	D1	Illinois, Williamson county.....	20	225	233	224	215	207	203	14.75	14.50
211	...	.....	20	450	458	446	430	418	416	20.25	31.00
217	...	.....	20	600	608	594	567	554	549	21.25	29.25
214	L2	Illinois, Williamson county.....	25	315	325	307	305	288	281	21.75	24.00
212	...	.....	25	525	535	516	502	484	476	40.00	27.50
218	...	.....	25	735	745	729	695	680	673	55.50	32.50
236	D1	Illinois, Macon county.....	20	300	308	297	276	266	259	24.75	21.00
234	...	.....	20	525	533	511	481	461	456	35.00	44.75
232	...	.....	20	750	758	737	678	659	650	57.25	50.75
237	D2	Illinois, Macon county.....	25	315	325	309	291	277	267	26.75	27.50
235	...	.....	25	630	640	616	578	556	545	44.25	51.75
233	...	.....	25	840	850	834	760	746	736	67.25	47.00
241	D1	Illinois, Vermilion county.....	20	225	233	226	206	199	194	17.00	14.00
243	...	.....	20	450	458	446	409	398	393	27.50	24.75
239	...	.....	20	675	683	669	605	593	588	37.00	35.75
242	D2	Illinois, Vermilion county.....	25	315	325	311	287	275	266	29.00	19.50
244	...	.....	25	525	535	522	478	467	457	36.50	26.75
240	...	.....	25	840	850	833	753	739	717	56.25	40.50

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(Continued)

Test Numb	Boiler	Kind of Fue	Proximate Analysis (per cent)									
			Fuel as Fired					Dry Fuel				
			Fixed Carbon	Volatile	Moisture	Ash	Sulphur	Fixed Carbon	Volatile	Ash	Sulphur	
			26	27	28	29	34	26	27	29	34	
162	D1	Anthracite.....	77.30	7.04	3.94	11.72	1.55	80.47	7.33	12.20	1.61	
166	.....	.....	77.54	7.06	3.64	11.76	1.56	80.47	7.33	12.20	1.62	
186	.....	.....	79.85	4.27	4.13	11.75	0.70	83.29	4.45	12.26	0.73	
163	D2	Anthracite.....	77.30	7.04	3.94	11.72	1.55	80.47	7.33	12.20	1.61	
167	.....	.....	77.54	7.06	3.64	11.76	1.56	80.47	7.33	12.20	1.62	
187	.....	.....	79.85	4.27	4.13	11.75	0.70	83.29	4.45	12.26	0.73	
172	D1	Pocahontas.....	73.36	19.50	1.97	5.17	0.98	74.83	19.89	5.28	1.00	
174	.....	.....	73.32	19.49	2.02	5.17	0.98	74.83	19.89	5.28	1.00	
176	.....	.....	73.32	19.49	2.02	5.17	0.98	74.83	19.89	5.28	1.00	
173	D2	Pocahontas.....	73.36	19.50	1.97	5.17	0.98	74.83	19.89	5.28	1.00	
175	.....	.....	73.32	19.49	2.02	5.17	0.98	74.83	19.89	5.28	1.00	
177	.....	.....	73.32	19.49	2.02	5.17	0.98	74.83	19.89	5.28	1.00	
178	D1	Gas House Coke.....	81.35	2.78	6.12	9.75	1.31	86.65	2.96	10.39	1.40	
199	.....	.....	78.57	3.37	7.35	10.71	1.07	84.80	3.64	11.56	1.15	
180	.....	.....	82.61	2.82	4.67	9.90	1.33	86.66	2.96	10.38	1.39	
213	.....	.....	82.20	4.26	4.65	8.89	0.99	86.21	4.47	9.32	1.04	
201	.....	.....	78.08	4.91	5.97	11.04	0.99	83.04	5.22	11.74	1.05	
182	.....	.....	80.79	2.76	6.76	9.69	1.30	86.65	2.96	10.39	1.39	
179	D2	Gas House Coke.....	80.28	2.74	7.36	9.62	1.30	86.66	2.96	10.38	1.40	
200	.....	.....	78.57	3.37	7.35	10.71	1.07	84.80	3.64	11.56	1.15	
181	.....	.....	82.61	2.82	4.67	9.90	1.33	86.66	2.96	10.38	1.39	
185	.....	.....	85.20	1.73	3.71	9.36	0.92	88.48	1.80	9.72	0.96	
183	.....	.....	80.79	2.76	6.76	9.69	1.30	86.65	2.96	10.39	1.39	
202	.....	.....	78.08	4.91	5.97	11.04	0.99	83.04	5.22	11.74	1.05	
197	D1	Solvay Coke.....	86.42	1.50	2.04	10.04	0.63	88.22	1.53	10.25	0.64	
195	.....	.....	86.22	2.04	1.93	9.81	0.64	87.92	2.08	10.00	0.65	
192	.....	.....	85.48	2.19	1.38	10.96	0.65	86.66	2.22	11.10	0.66	

	D2	Solvey Coke.....	85.63	2.70	1.31	10.36	0.66	86.76	2.74	10.50	0.67
207	.....	.....	86.22	2.04	1.33	9.81	0.64	87.32	2.08	10.00	0.65
196	.....	.....	86.46	2.19	1.38	10.35	0.65	86.08	2.22	11.10	0.66
215	D1	Illinois, Williamson county.....	49.60	34.20	7.83	8.37	1.92	53.81	37.11	9.08	2.08
211	.....	.....	46.86	38.48	6.21	8.45	2.23	49.36	41.03	9.01	2.38
217	.....	.....	48.85	34.68	6.69	9.68	2.04	52.46	37.17	10.37	2.19
214	D2	Illinois, Williamson county.....	47.03	37.60	6.10	9.27	1.99	50.09	40.04	9.87	2.12
212	.....	.....	46.86	38.48	6.21	8.45	2.23	49.36	41.03	9.01	2.38
218	.....	.....	48.85	34.68	6.69	9.68	2.04	52.46	37.17	10.37	2.19
236	D1	Illinois, Macon county.....	39.04	38.21	10.45	12.30	2.95	43.60	42.67	13.73	3.29
234	.....	.....	39.95	38.25	9.74	12.06	3.20	44.26	42.38	13.36	3.55
232	.....	.....	41.34	36.84	10.53	11.29	3.21	46.20	41.18	12.62	3.68
237	D2	Illinois, Macon county.....	39.04	38.21	10.45	12.30	2.95	43.60	42.67	13.73	3.29
235	.....	.....	39.95	38.25	9.74	12.06	3.21	44.26	42.38	13.36	3.55
233	.....	.....	41.34	36.84	10.53	11.29	3.21	46.20	41.18	12.62	3.68
241	D1	Illinois, Vermillion county.....	40.27	38.65	11.54	9.54	2.25	45.32	43.69	10.79	2.54
243	.....	.....	40.91	40.85	10.63	7.61	1.61	45.78	45.71	8.51	1.80
239	.....	.....	40.03	39.01	11.40	9.56	2.57	45.18	44.03	10.79	2.90
212	D2	Illinois, Vermillion county.....	40.27	38.65	11.54	9.54	2.25	45.32	43.69	10.79	2.54
214	.....	.....	40.91	40.85	10.63	7.61	1.61	45.78	45.71	8.51	1.80
240	.....	.....	40.03	39.01	11.40	9.56	2.57	45.18	44.03	10.79	2.90

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(Continued)

Test Number	Boiler	Kind of Fuel	Residual Fuel (per cent)		Ash (per cent)		Dry Fuel per Hour		B. t. u. per Pound Fuel	
			Carbon	Earthy Matter	Carbon	Earthy Matter	Pounds	Per Sq. Ft. of Grate Surface	Dry	As Fired
			37	38	40	41	43	44	45	46
162	D1	Anthracite.....	70.50	29.50	46.07	53.93	24.29	5.68	13219	12698
166	.....	.....	66.82	33.18	38.45	61.55	22.72	5.31	13218	12737
186	.....	.....	65.01	34.99	36.76	63.24	22.07	5.16	13179	12635
163	D2	Anthracite.....	76.65	23.35	62.98	37.02	27.00	4.50	13219	12698
167	.....	.....	70.18	29.82	49.26	50.74	24.53	4.14	13218	12737
187	.....	.....	65.13	34.87	44.78	55.22	23.46	3.91	13179	12635
172	D1	Pocahontas.....	65.71	34.29	67.91	32.09	21.15	4.94	15055	14758
174	.....	.....	50.36	49.64	50.10	49.90	21.20	4.95	15055	14751
176	.....	.....	37.15	62.85	57.11	42.89	23.24	5.43	15055	14751
173	D2	Pocahontas.....	63.06	36.94	70.31	29.69	23.48	3.91	15055	14751
175	.....	.....	66.18	33.82	66.53	33.47	24.80	4.13	15055	14751
177	.....	.....	63.69	36.31	62.78	37.22	23.45	3.91	15055	14751
178	D1	Gas House Coke.....	46.71	53.29	34.66	65.34	24.20	5.65	12805	11698
199	.....	.....	49.05	50.95	23.76	71.24	21.00	4.91	12826	12021
180	.....	.....	38.11	61.89	18.89	81.11	22.05	5.15	12804	12206
213	.....	.....	44.06	55.94	15.53	84.47	20.23	4.73	12647	12059
201	.....	.....	38.41	61.59	18.05	81.95	20.46	4.78	12647	12112
182	.....	.....	54.06	45.94	9.61	90.39	20.63	4.62	12805	11939
179	D2	Gas House Coke.....	57.30	42.70	35.55	64.45	23.50	3.92	12804	11862
200	.....	.....	43.48	56.52	36.49	63.51	23.31	3.87	12636	11698
181	.....	.....	54.55	45.45	29.45	70.55	25.34	4.22	12804	12206
185	.....	.....	47.17	52.83	38.66	61.34	24.82	4.14	13028	12545
183	.....	.....	56.47	43.53	12.93	87.07	22.66	3.78	13805	11939
202	.....	.....	44.71	55.29	19.45	80.55	23.87	3.98	12881	12112
197	D1	Solvay Coke.....	46.43	53.57	31.98	68.02	19.94	4.66	12636	12378
195	.....	.....	45.65	54.35	10.10	89.90	18.79	4.39	12632	12378
192	.....	.....	37.37	62.63	8.65	91.35	19.15	4.47	12745	12669

	D2	Solvay Coke.		46.87	37.37	72.63	23.03	2.95	12885	12655
207	...	...	...	53.13	26.96	73.04	24.26	4.01	12622	12655
196	...	...	...	52.04	31.98	68.02	23.52	3.92	12715	12678
193	...	...	...	44.29	23.84	76.16	23.99	5.61	13227	12769
215	D1	Illinois, Williamson county	...	50.90	9.69	90.31	23.64	5.52	13207	12911
211	...	...	...	34.06	11.35	88.65	23.59	5.51	13079	12887
217	...	...	...	40.74	59.26	37.12	29.15	4.86	13092	12204
214	D2	Illinois, Williamson county	...	62.88	30.85	69.15	29.15	4.86	13092	12223
212	...	...	...	58.02	18.44	81.56	31.07	5.18	13207	12387
218	...	...	...	40.02	11.90	88.10	29.34	4.89	13079	12204
236	D1	Illinois, Macon county	...	39.51	25.02	74.98	27.20	6.36	12312	11025
234	...	...	...	37.88	69.12	87.31	27.56	6.44	12216	11017
232	...	...	...	31.18	68.82	87.40	26.81	6.26	12262	10989
237	D2	Illinois, Macon county	...	42.83	30.07	69.93	33.05	5.51	12312	11025
235	...	...	...	34.76	67.17	79.79	34.68	5.78	12216	11017
233	...	...	...	25.01	74.99	86.93	32.25	5.88	122-2	10989
241	D1	Illinois, Vermillion county	...	41.04	58.96	72.39	24.97	5.83	12878	11382
243	...	...	...	30.07	59.96	84.07	24.19	5.65	13251	11411
239	...	...	...	40.04	69.93	88.04	24.23	5.66	12879	11411
242	...	...	...	54.06	45.94	73.24	32.16	5.36	12878	11382
244	D2	Illinois, Vermillion county	...	38.15	61.85	75.51	30.99	5.17	13251	11842
240	...	...	...	51.26	48.74	81.11	29.14	4.86	12879	11411

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS, MADE AT
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(Continued)

Test Number	Boiler	Kind of Fuel	Moisture in Steam (per cent)	Factor for Correcting Quality of Steam	Water (pounds)			Factor of Evaporation	Equivalent		Water Per Hour (pounds)
					Fed to Boiler	Corrected for Quality of Steam	Equivalent from and at 212° F.		Equivalent from and at 212° F. Surface Water-heating		
			47	48	49	50	52	51	53	54	
162	D1	Anthracite.....	0.96	.9912	1349	1337	1397	1.0450	159	3.64	
166		.....	0.93	.9914	2518	2496	2608	1.0450	158	3.62	
186		.....	1.10	.9898	3568	3532	3665	1.0376	158	3.62	
163	D2	Anthracite.....	0.68	.9937	1577	1567	1633	1.0419	204	2.69	
167		.....	0.61	.9944	3432	3413	3559	1.0428	203	2.68	
187		.....	0.88	.9918	4960	4919	5104	1.0376	196	2.58	
172	D1	Pocahontas.....	1.00	.9909	1423	1410	1484	1.0522	147	3.36	
174		.....	1.07	.9902	2460	2436	2547	1.0456	150	3.43	
176		.....	1.03	.9905	3863	3825	4085	1.0407	163	3.73	
173	D2	Pocahontas.....	0.69	.9937	2372	2357	2500	1.0606	198	2.61	
175		.....	0.95	.9913	3946	3924	3404	1.0450	212	2.79	
177		.....	0.77	.9929	5261	5224	5448	1.0428	210	2.77	
178	D1	Gas House Coke.....	1.05	.9904	1387	1374	1443	1.0501	171	3.91	
199		.....	0.99	.9908	1404	1391	1445	1.0387	151	3.46	
180		.....	1.04	.9904	2393	2370	2466	1.0407	156	3.57	
213		.....	1.06	.9902	2513	2488	2602	1.0460	152	3.48	
201		.....	1.18	.9891	3538	3499	3653	1.0439	154	3.52	
182		.....	1.08	.9900	4047	4007	4170	1.0407	159	3.64	
179	D2	Gas House Coke.....	0.84	.9922	2287	2269	2364	1.0419	202	2.66	
200		.....	0.80	.9926	2307	2280	2383	1.0407	201	2.65	
181		.....	0.80	.9928	2954	2933	3059	1.0428	205	2.70	
185		.....	0.78	.9926	3012	2990	3202	1.0710	206	2.72	
183		.....	0.75	.9931	4731	4698	4899	1.0428	197	2.60	
202		.....	0.93	.9914	4634	4594	4781	1.0407	198	2.61	
197	D1	Solway Coke.....	1.01	.9906	1629	1614	1675	1.0376	158	3.62	
195		.....	1.05	.9903	2270	2248	2333	1.0376	154	3.52	
192		.....	1.12	.9896	3940	3899	4042	1.0366	152	3.48	

D ₂	Solvay Coke	0.87	.9919	2.44	3411	2504	1.0387	199	2.62
307	.....	0.85	.9921	3179	3411	3276	1.0387	201	2.65
196	.....	0.86	.9920	4681	3154	4799	1.0334	188	2.48
193	Illinois, Williamson county	0.98	.9909	1282	4614	1312	1.0334	152	3.45
215	.....	1.09	.9900	2594	5270	2697	1.0501	153	3.50
211	.....	1.09	.9899	3559	5523	3674	1.0428	156	3.57
217	Illinois, Williamson county	1.01	.9906	1982	1963	2129	1.0334	205	2.70
214	.....	1.01	.9907	3160	3131	3268	1.0439	210	2.77
212	.....	1.03	.9905	4761	4716	4908	1.0407	212	2.79
218	Illinois, Macon county	0.95	.9912	1494	1481	1540	1.0397	157	3.53
236	.....	0.93	.9914	2598	2576	2676	1.0387	160	3.56
234	.....	0.95	.9912	3719	3676	3821	1.0366	155	3.55
232	Illinois, Macon county	0.61	.9943	1778	1768	1833	1.0366	219	2.89
237	.....	0.77	.9936	3394	3270	3376	1.0324	211	2.78
235	.....	0.77	.9928	4643	4610	4759	1.0324	206	2.72
233	Illinois, Vermilion county	0.98	.9940	1205	1194	1250	1.0471	157	3.59
241	.....	1.00	.9908	2488	2465	2578	1.0460	157	3.59
243	.....	0.97	.9910	3718	3685	3835	1.0407	157	3.59
239	Illinois, Vermilion county	0.70	.9935	1801	1759	1858	1.0387	217	2.86
242	.....	0.68	.9937	3144	3124	3225	1.0324	214	2.82
244	.....	0.75	.9930	4593	4859	5037	1.0363	201	2.65
240	.....								

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS MADE AT
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(Continued)

Test Number	Boiler	Kind of Fuel	Mean Load Carried		Percentage of Rated Capacity Developed (per cent)	Economic Results (pounds)			
			Sq. Ft. of Radiating Surface	Sq. Ft. of Radiating Surface plus Surface of Boiler		Equivalent Evaporation from and at 212° F. per pound		Fuel per Hour per 100 Sq. Ft. of Radiating Surface	
						Fuel as Fired	Dry Fuel Consumed	As Fired	Dry
			55	55.1	56	57	58	59	60
162	D1	Anthracite	530	568	66.25	6.32	6.75	4.75	4.58
166			527	565	65.88	6.67	7.15	4.48	4.31
186			527	565	65.88	6.63	7.40	4.37	4.19
163	D2	Anthracite	680	783	63.26	7.26	7.93	4.14	3.97
167			677	780	62.96	7.87	8.60	3.81	3.67
187			653	756	60.74	8.01	8.70	3.75	3.59
172	D1	Pocahontas	496	528	61.25	6.84	7.27	4.40	4.32
174			500	538	62.50	6.90	7.24	4.33	4.24
176			543	581	67.88	6.87	7.24	4.36	4.28
173	D2	Pocahontas	660	763	61.40	8.25	9.03	3.63	3.56
175			707	810	65.77	8.38	9.01	3.58	3.51
177			700	803	65.11	8.77	9.38	3.42	3.35
178	D1	Gas House Coke	570	608	71.25	6.65	7.16	4.52	4.25
199			503	541	62.88	6.69	7.34	4.49	4.17
180			520	558	65.00	6.74	7.11	4.45	4.24
213			507	545	63.38	7.15	7.56	4.19	3.99
201			513	551	64.13	7.08	7.63	4.24	3.99
182			530	568	66.25	7.19	7.73	4.17	3.89
179	D2	Gas House Coke	673	776	62.60	7.39	8.76	3.76	3.49
200			670	773	62.53	8.02	8.89	3.74	3.46
181			683	786	63.53	7.72	8.20	3.89	3.71
185			687	790	63.91	7.99	8.38	3.75	3.61
183			657	760	61.12	8.12	8.76	3.69	3.45
202			660	763	61.40	7.80	8.40	3.84	3.62
197	D1	Solvay Coke	527	565	65.88	7.75	8.05	3.86	3.78
195			513	551	64.13	8.02	8.21	3.71	3.63
192			507	545	63.38	7.85	7.99	3.83	3.78

207	D2	Solvay Coke.....	663	766	61.67	8.29	8.55	3.62	3.57
196	.....	.....	670	773	62.33	8.11	8.44	3.70	3.62
153	.....	.....	627	730	58.33	7.87	8.13	3.81	3.75
215	D1	Illinois, Williamson county	507	545	63.38	5.86	6.46	5.12	4.73
211	.....	.....	510	548	63.75	6.05	6.48	4.95	4.64
217	.....	.....	520	558	65.00	6.19	6.69	4.86	4.54
214	D2	Illinois, Williamson county	683	786	63.53	6.61	7.22	4.55	4.27
212	.....	.....	700	803	65.12	6.33	6.87	4.75	4.44
218	.....	.....	707	810	65.77	6.73	7.29	4.45	4.15
236	D1	Illinois, Macon county	533	561	65.40	5.19	5.95	5.81	5.20
234	.....	.....	533	571	66.63	5.24	5.87	5.73	5.17
232	.....	.....	517	555	64.60	5.18	5.88	5.60	5.19
237	D2	Illinois, Macon county	730	833	67.91	5.93	6.87	5.07	4.55
235	.....	.....	687	806	65.40	5.46	6.19	5.47	4.93
241	.....	.....	687	790	63.91	5.71	6.47	5.25	4.69
243	D1	Illinois, Vermilion county	523	561	65.40	5.53	6.44	5.32	4.77
239	.....	.....	520	558	65.00	5.78	6.56	5.21	4.65
242	D2	Illinois, Vermilion county	723	826	65.00	5.73	6.52	5.26	4.66
244	.....	.....	713	816	67.30	5.97	6.98	5.03	4.45
240	.....	.....	670	773	66.30	6.18	7.06	4.86	4.35
	.....	.....			62.30	6.12	7.03	4.91	4.35

TABLE 12 HOUSE-HEATING BOILER TESTS WITH REPRESENTATIVE FUELS MADE AT
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS, URBANA—(Continued)

Test Number	Boiler	Kind of Fuel	Efficiency (per cent)		Fuel \$1.00 per 2000 lb.		Fuel Fired at Each Firing (pounds)	Average Interval (hours)		Maximum Interval of Steam Pressure With- out Attention
			Boiler and Furnace	Plant	Cost in Cents per 100 sq. ft. of Radi- ating Surface per hour (Mean Load Carried on Test)	Cost of Evapo- rating 1000 lb. of Water from and at 212° F. (cents)		Between Firings	Between Times of Shaking and Raking	
			61	62	64	65	70	71	72	73
102	D1	Anthracite	49.32	48.07	.238	7.91	75	2.19	2.19	3.17
106		.....	52.24	50.58	.224	7.50	75	2.76	1.84	3.43
166		.....	54.23	52.59	.219	7.27	75	2.47	2.19	3.00
163	D2	Anthracite	57.94	55.22	.207	6.89	105	2.67	2.00	4.55
167		.....	62.84	59.68	.191	6.35	105	3.50	1.95	3.67
187		.....	63.76	61.23	.188	6.24	105	3.71	2.89	4.67
172	D1	Pocahontas	46.64	44.76	.320	7.31	75	3.36	1.01	1.87
174		.....	46.45	45.18	.217	7.24	75	3.41	0.71	2.00
176		.....	46.45	44.98	.218	7.28	75	3.14	0.63	1.20
173	D2	Pocahontas	57.93	53.99	.182	6.06	105	4.22	0.84	2.63
175		.....	57.80	54.87	.179	5.97	105	4.01	1.00	2.60
177		.....	60.17	57.42	.171	5.70	105	4.32	0.93	2.82
178	D1	Gas House Coke	54.15	53.43	.226	7.52	75	2.81	2.81	1.70
199		.....	56.15	55.23	.225	7.47	75	3.19	2.39	3.00
180		.....	53.63	53.33	.223	7.42	75	3.17	3.17	3.00
213		.....	57.73	57.26	.210	6.99	75	3.43	3.43	3.33
201		.....	57.21	56.46	.212	7.06	75	3.43	2.63	3.33
182		.....	58.45	58.16	.209	6.95	75	3.28	3.28	3.00
179	D2	Gas House Coke	66.08	65.05	.188	6.26	105	3.90	2.34	3.00
200		.....	68.00	66.21	.187	6.23	105	3.95	1.98	3.00
181		.....	61.85	61.08	.185	6.48	105	3.73	2.13	3.33
185		.....	62.12	61.51	.188	6.26	105	3.73	1.95	3.33
183		.....	66.07	65.69	.185	6.16	105	4.14	4.14	4.10
202		.....	62.98	62.20	.192	6.41	105	4.03	2.42	4.00
197	D1	Solvay Coke	61.53	60.47	.193	6.45	75	3.54	3.54	3.66
195		.....	62.82	62.58	.186	6.23	75	3.79	3.79	3.79
192		.....	60.55	60.32	.192	6.37	75	3.79	3.79	3.66

207	D2	Solway Coke.....	64.40	63.27	181	6.03	105	4.19	2.52	3.38
196	...	...	64.58	63.98	.185	6.17	105	4.08	3.26	4.00
193	...	...	61.61	60.37	.191	6.35	105	4.20	2.84	4.00
215	D1	Illinois, Williamson county	47.17	46.42	.256	8.53	75	2.88	1.08	1.33
211	...	...	47.39	47.17	.248	8.26	75	2.95	1.47	1.66
217	...	...	49.40	48.99	.243	8.08	75	2.93	0.84	1.33
214	D2	Illinois, Williamson county	53.26	51.93	.228	7.56	105	3.29	1.41	2.00
212	...	...	50.24	49.35	.237	7.90	105	3.12	1.42	2.00
218	...	...	53.83	53.26	.223	7.43	105	3.31	1.01	2.00
236	D1	Illinois, Macon county	46.67	45.46	.291	9.65	75	2.45	0.98	1.33
234	...	...	46.45	45.94	.287	9.56	75	2.39	1.05	1.66
232	...	...	46.24	45.53	.290	9.67	75	2.46	0.95	1.66
235	D2	Illinois, Macon county	53.89	51.95	.254	8.43	105	2.79	1.05	1.66
232	...	...	48.98	48.04	.275	9.12	105	2.67	1.14	1.33
233	...	...	50.88	50.18	.263	8.77	105	2.89	1.16	2.00
241	D1	Illinois, Vermilion county	48.30	46.99	.271	9.06	75	2.66	0.66	1.00
243	...	...	47.81	47.14	.261	8.67	75	2.74	0.97	1.33
239	...	...	48.89	48.50	.263	8.74	75	2.72	0.94	1.66
242	D2	Illinois, Vermilion county	52.35	50.51	.252	8.38	105	2.85	0.86	0.66
244	...	...	51.46	50.40	.243	8.09	105	3.01	1.16	1.66
240	...	...	52.72	51.80	.246	8.17	105	3.13	1.04	1.33

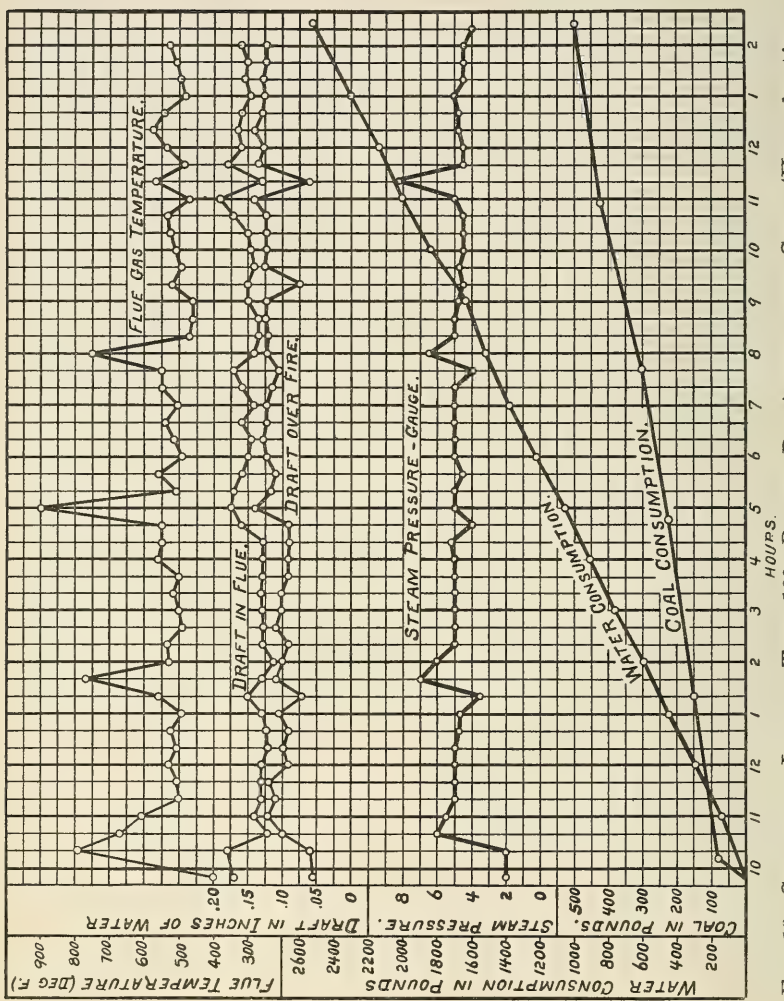


FIG. 18 GRAPHICAL LOG FOR TEST 166—BOILER D₁—ANTHRACITE COAL (House-heating boiler tests with representative fuels). (See "6. Test Data," p. 20).

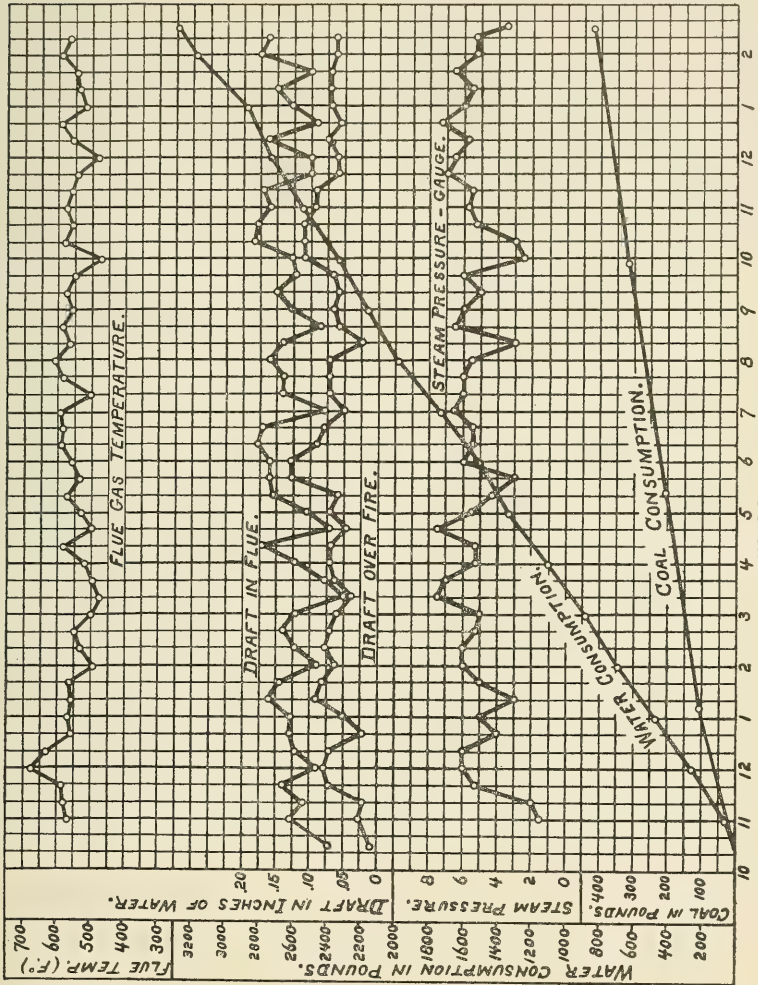
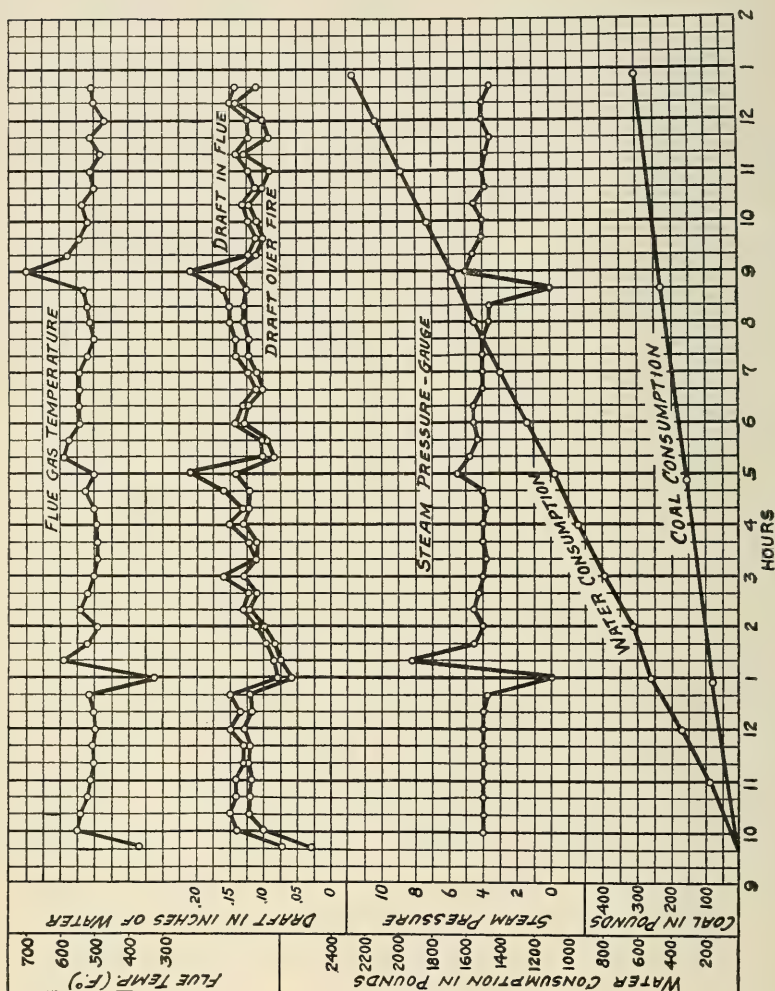


FIG. 19 GRAPHICAL LOG FOR TEST 175—BOILER D₂—POCAHONTAS COAL

FIG. 20 GRAPHICAL LOG FOR TEST 195---BOILER D₁---SOLVAY COKE

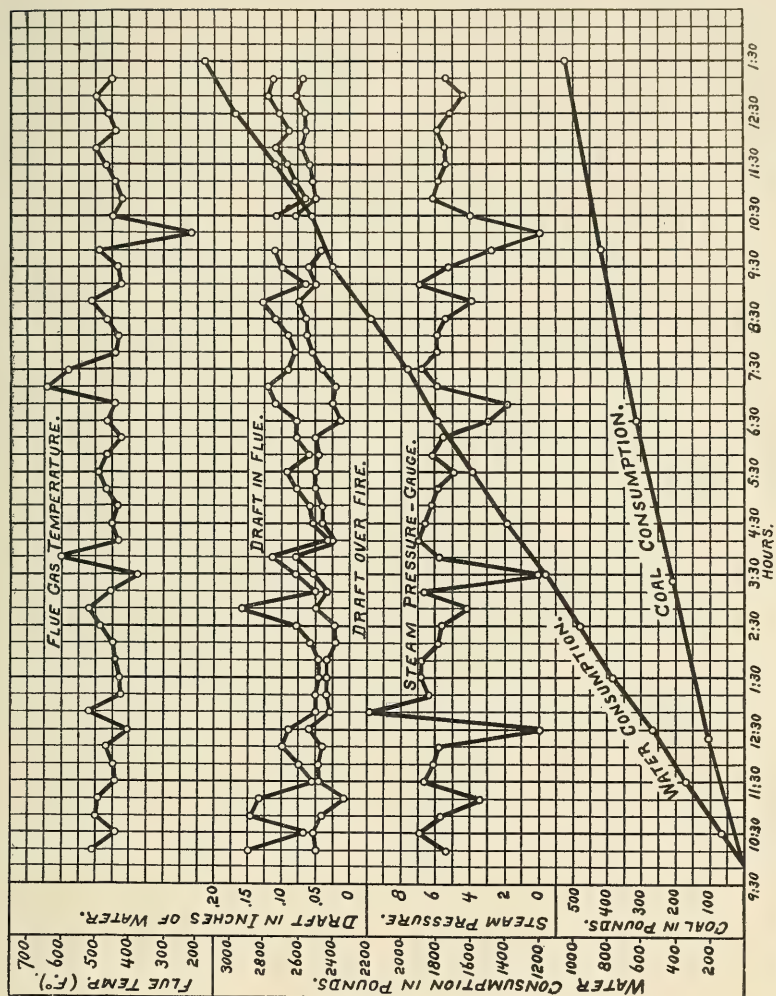


FIG. 21 GRAPHICAL LOG FOR TEST 212—BOILER D₂—ILLINOIS COAL (Williamson Co.)

TABLE 13

**FLUE GAS ANALYSES, HOUSE-HEATING BOILER TRIALS WITH
REPRESENTATIVE FUELS***

Kind of Fuel	Test No.	Length of Test (hours)	CO2 per cent	O2 per cent	Average	
					CO2 per cent	O2 per cent
BOILER D1						
Anthracite.....	162	8.76	3.6	14.6		
.....	186	23.15	6.4	11.4	5.0	13.0
Pocahontas.....	176	25.13	3.5	16.2	3.5	16.2
Gas House Coke.....	199	9.57	9.4	11.1		
.....	180	15.83	3.7	16.0		
.....	201	23.70	8.2	12.2		
.....	182	26.23	6.0	13.5	6.8	13.2
Solvay Coke.....	197	10.63	9.1	11.3		
.....	195	15.17	8.3	12.0	8.7	11.7
Illinois, Williamson county.....	215	8.63	6.7	12.8		
.....	217	23.48	6.8	12.8	6.8	12.8
Illinois, Macon county.....	234	16.73	6.2	13.4	6.2	13.4
BOILER D2						
Anthracite.....	163	8.00	8.8	10.7		
.....	167	17.52	9.9	9.7		
.....	187	26.00	8.9	9.6	9.2	10.0
Pocahontas.....	175	16.05	7.6	10.1		
.....	177	25.93	8.7	9.3	8.2	9.7
Gas House Coke.....	179	11.70	9.3	7.4		
.....	200	11.85	15.3	4.4		
.....	185	15.55	14.4	5.0		
.....	181	14.92	12.0	6.7		
.....	183	24.85	11.7	6.9		
.....	202	24.17	13.5	6.3	12.7	6.1
Solvay Coke.....	209	12.57	14.3	4.7		
.....	196	16.33	12.1	7.3	13.2	6.0
Illinois, Williamson county.....	214	9.88	10.4	6.7		
.....	212	15.58	11.7	4.5		
.....	218	23.18	5.1	14.8	9.1	8.7
Illinois, Macon county.....	235	16.03	11.4	5.9	11.4	5.9

*See "7. Tabulated Data and Results," p. 20.

TABLE 14

COMPARISON OF FLUE GAS ANALYSES TAKEN AT DIFFERENT TIMES
DURING TEST, BOILER D₂, HOUSE-HEATING BOILER TRIALS
WITH REPRESENTATIVE FUELS

Fuel	Time of Starting Sample	Length of Time of Collecting Sample (min.)	When Taken	CO ₂ per cent	O ₂ per cent
Anthracite	10:00 A. M.	20	Just after 2nd firing.....	7.2	9.6
	11:00 A. M.	35	1 hour after 2nd firing.....	9.0	10.0
	12:00 M.	45	2 hours after 2nd firing.....	8.4	10.4
	2:05 P. M.	60	45 minutes after 3rd firing.....	11.1	7.9
Gas House Coke	9:45 A. M.	60	37 minutes after 1st firing.....	14.0	5.7
	12:25 P. M.	60	15 minutes after 2nd firing.....	14.4	3.9
	2:10 P. M.	80	2 hours after 2nd firing.....	14.8	5.3
	4:20 P. M.	20	2 minutes after 3rd firing.....	11.3	7.3
	5:10 P. M.	30	52 minutes after 3rd firing.....	16.5	3.6
	6:00 P. M.	60	1 hour 42 min. after 3rd firing....	15.6	4.4
Solvay Coke	9:15 A. M.	45	1 hour after 1st firing*.	15.1	4.1
	10:45 A. M.	30	2 hours 30 min. after 1st firing**	12.2	7.0
	10:00 A. M.	60	47 minutes after 1st firing.....	13.8	5.6
	12:00 M.	60	2nd firing at 12:45.	10.8	9.2
	2:35 P. M.	60	1 hour 50 min. after 2nd firing..	13.2	4.6
	4:30 P. M.	40	3 hours 45 min. after 2nd firing...	10.5	9.8
Illinois, Williamson county	9:25 A. M.	30	30 minutes after 1st firing†.....	7.9	9.8
	10:00 A. M.	30	65 minutes after 1st firing††.....	9.7	8.1
	11:52 A. M.	30	Just after 2nd firing.....	8.0	8.7
	12:30 P. M.	30	40 minutes after 2nd firing.....	12.4	4.6
	2:30 P. M.	34	1 hour before 3rd firing.....	13.3	6.2
	3:35 P. M.	..	Just after 3rd firing.....	11.4	2.8

* Fire hot and thick. ** Fire thin, with several holes.

Both of these samples on test No. 207. Other four coke samples on test No. 196.

† Fire badly caked. †† Fire clear and bright.

TABLE 15

**SMOKE CHART RECORD, HOUSE-HEATING BOILER TRIALS
WITH REPRESENTATIVE FUELS**

Boiler No.	Kind of Fuel	Test No.	Number of Firing after which Smoke Record was Made	Color or Condition of Smoke	Maximum Density of Smoke Recorded		Percent of Firing Interval During Which Smoke Was Produced	Percent of Firing Interval During Which No Smoke Was Produced	Percent of Black Smoke for Test Based Upon the Intervals Observed
					per cent	No. on Ringelmann Chart			
D1	Gas House Coke.....	199	3rd	.....	40	2	7	93	2
D1	"	213	1st	Dense Yellow	50	2.5	9	91	3
D2	"	200	3rd	.....	20	1	7	93	1
D2	"	185	3rd	.....	40	2	6	94	2
D1	Solvay Coke.	195	1st	Gray Yellow.....	50	2.5	7	93	2
D1	"	192	2d & 6th	Light Gray.	10	0.5	5	95	0
D2	"	196	1st	Light Yellow.....	50	2.5	10	90	3
D2	"	193	1st	Light Gray.	60	3	15	85	3
D1	Williamson county, Illinois.....	211	3rd	.....	40	2	50	50	14
D1	"	217	2nd	Yellow, black, gray	70	3.5	49	51	11
D2	"	214	1st	.....	60	3	48	52	13
D1	Macon county, Illinois....	236	2nd	.....	70	3.5	48	52	16
D1	"	234	2nd	.....	40	2	40	60	13
D1	"	232	2nd	.....	50	2.5	64	36	24
D2	"	237	2nd	.....	60	3	61	39	22
D2	"	235	2nd	.....	60	3	44	56	17
D2	"	233	2nd	.....	60	3	27	73	10
D1	Vermilion county, Illinois.....	241	3rd	.....	60	3	44	56	18
D1	"	243	4th	.....	50	2.5	34	66	13
D1	"	239	2nd	.....	60	3	56	44	24
D2	"	242	3rd	.....	70	3.5	60	40	23
D2	"	244	4th	.....	60	3	50	50	15
D2	"	240	2nd	.....	50	2.5	45	55	16

APPENDIX B

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT ST. LOUIS*

Test No.	Designation of Fuel	Description of Fuel	Duration of Trial hours	Average Pressures				
				Steam Pressure in Boiler (gauge)	Barometer (lb. per sq. in.)	Draft in. of water		
						Between Damper and Boiler	Over Fire	In Ashpit
			1	10	11.1	12	13	13.1
45	Arkansas No. 13	Briquets, round.	8.33	2.2	14.39	0.34	0.07	0.04
58	Illinois No. 1	Coal, run-of-mine	7.92	1.9	14.36	.33	.07	.03
59	Illinois No. 1	Coal, run-of-mine	8.00	1.9	14.45	.36	.05	.03
48	Illinois No. 7 E	Briquets, round.	8.00	1.7	14.45	.33	.06	.03
39	Illinois No. 9 C	Briquets, round.	8.30	1.7	14.54	.36	.07	.04
13	Illinois No. 12 B W	Briquet, square, slack	8.25	3.8	14.39	.21	.06	.05
52	Illinois No. 19 E	Coal, egg	7.80	2.4	14.56	.31	.03	.03
53	"	"	8.25	2.3	14.41	.35	.05	.04
54	"	"	8.06	2.1	14.30	.32	.03	.02
55	"	"	7.83	1.3	14.35	.36	.03	.02
9	Illinois No. 29 A W	Briquets, round.	7.88	3.4	14.46	.24	.10	.06
12	Illinois No. 29 B	Briquets, round, slack	7.20	2.2	14.51	.23	.08	.07
33	Illinois No. 31	Briquets, square	7.83	2.7	14.37	.29	.13	.10
34	"	"	8.08	2.9	14.34	.28	.10	.06
44	"	Briquets, round.	8.33	1.8	14.40	.36	.07	.04
43	Illinois No. 33	"	7.83	2.2	14.34	.32	.08	.05
37	Indiana No. 1 B	"	8.33	2.4	14.60	.35	.13	.07
36	Indiana No. 5 B	"	8.41	2.7	14.26	.34	.13	.08
38	Indiana No. 6 B	Briquets, square	7.88	2.8	14.64	.35	.09	.06
10	Indian Territory No. 2 B W	Briquets, square, slack	7.92	3.3	14.59	.25	.12	....
11	Indian Territory No. 2 B	Briquets, round, slack	7.87	4.3	14.51	.22	.05	.04
1	Kansas No. 2 B	"	8.00	4.1	14.46	.22	.05	.03
40	"	Briquets, square	8.25	2.5	14.38	.36	.09	.06
21	Maryland No. 2	Briquets, round	8.00	2.9	14.65	.28	.12	.09
22	"	"	7.50	3.2	14.55	.23	.11	.10
23	"	"	8.00	3.6	14.51	.23	.11	.10
20	"	Coal, run-of-mine	7.88	2.2	14.52	.25	.13	.09
2	Missouri No. 10	Briquets, round, slack	7.66	3.4	14.68	.24	.04	.03
3	"	"	7.83	3.1	14.46	.21	.07	.05
4	"	"	7.82	3.2	14.54	.25	.08	.06
5	"	"	8.13	2.0	14.59	.26	.10	.05
28	Pennsylvania No. 18	Briquets, round.	8.00	3.9	14.37	.18	.09	.08
29	"	"	8.00	4.6	14.44	.18	.07	.06
30	"	Briquets, square	7.70	3.3	14.51	.22	.11	.10
31	"	"	8.00	3.4	14.60	.29	.12	.10
46	"	"	8.13	2.1	14.40	.36	.03	.01
24	"	Coal, run-of-mine	8.00	3.0	14.55	.22	.10	.09
25	"	"	8.00	3.1	14.41	.22	.13	....
32	Pennsylvania No. 19	Briquets, round.	6.58	3.6	14.33	.27	.11	.07
15	"	Coal, run-of-mine	7.50	3.4	14.43	.23	.11	.10
26	Pennsylvania No. 20	Briquets, square	8.00	3.4	14.48	.23	.12	....
27	"	"	8.00	3.3	14.40	.22	.11	....
41	Pennsylvania No. 20 W	Briquets, round	7.81	3.3	14.30	.32	.07	.06
42	"	"	5.20	2.9	14.32	.33	.09	.08
16	Pennsylvania No. 22	"	7.83	3.7	14.46	.22	.11	.08
17	"	"	8.08	3.5	14.28	.21	.09	.08
18	"	Briquets, square	8.00	1.6	14.36	.23	.09	.07
19	"	"	8.05	2.4	14.36	.23	.12	.11
14	"	Coal, run-of-mine	7.58	3.8	14.55	.23	.10	.07
47	Pennsylvania No. 15 (one half) and Rhode Island No. 1 (one-half)	Briquets, round	8.23	2.0	14.51	.34	.07	.03
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths)	"	8.16	1.6	14.38	.34	.04	.02
57	"	"	7.00	2.2	14.47	.36	.07	.04
35	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half)	"	5.66	3.2	14.31	.29	.10	.07
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth)	"	8.23	3.0	14.45	.30	.06	.04
50	Pennsylvania No. 18 (one-half) and Miscellaneous No. 9 (one-half)	"	7.83	2.2	14.40	.34	.07	.04
51	"	"	8.00	2.5	14.46	.33	.04	.02
7	Virginia No. 5 B	"	8.00	3.6	14.46	.24	.12	.10
8	"	"	7.80	4.8	14.35	.19	.09	.07

*See '15. Data and Results,' p. 58.

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT
ST. LOUIS—(Continued)

Test No.	Designation of Fuel	Average Temperature (°F)				Fuel as Fired pounds	Dry Fuel pounds	Total Dry Fuel Fired minus Dry Fuel Equiva- lent to the Carbon in the Ash pounds	Total Ash and Refuse from Ashpit (pounds)
		External Air	Boiler Room	Feed Water in Weigh Tank	Gases Escaping from Boiler				
		14	15	16	17	21	23	23.2	24
45	Arkansas No. 13.....	50	81	145	695	777	765	731	137
58	Illinois No. 1.....	64	88	121	710	854	739	706	151
59	.....	46	73	126	720	874	756	728	128
48	Illinois No. 7 E.....	45	77	141	650	965	907	874	237
39	Illinois No. 9 C.....	58	83	137	855	871	824	789	195
13	Illinois No. 12 BW.....	69	92	143	...	666	613	587	98
52	Illinois No. 19 E.....	59	88	138	600	817	757	727	114
53	.....	66	88	128	720	927	859	827	122
54	.....	62	85	135	635	811	752	725	104
55	.....	72	93	122	850	764	708	685	87
9	Illinois No. 29 A W.....	31	70	149	...	750	658	648	68
12	Illinois No. 29 B.....	46	79	147	...	735	688	671	106
33	Illinois No. 31.....	80	91	106	570	813	738	725	112
34	.....	82	96	101	400	836	759	743	139
44	.....	51	82	138	795	968	901	880	144
43	Illinois No. 33.....	50	81	146	600	974	882	761	333
37	Indiana No. 1 B.....	57	91	120	815	1104	1056	1037	120
36	Indiana No. 5 B.....	63	90	103	730	929	890	868	134
38	Indiana No. 6 B.....	45	82	140	715	815	768	750	144
10	Indian Territory No. 2 BW.....	33	71	150	...	736	720	686	100
11	Indian Territory No. 2 B.....	42	76	158	...	737	721	700	126
1	Kansas No. 2 B.....	40	72	145	...	667	648	...	113
40	.....	48	84	135	665	800	772	743	172
21	Maryland No. 2.....	31	74	150	...	652	628	612	73
22	.....	30	80	140	...	560	540	534	28
23	.....	41	73	143	...	650	626	611	67
20	.....	32	71	144	...	520	511	502	34
2	Missouri No. 10.....	32	70	151	...	1159	1031	986	258
3	.....	57	83	149	...	769	684	651	189
4	.....	27	69	139	...	819	729	695	193
5	.....	18	67	154	...	1036	922	898	136
28	Pennsylvania No. 18.....	46	81	140	...	580	537	531	37
29	.....	54	85	144	...	662	604	598	34
30	.....	42	83	146	...	525	500	496	31
31	.....	58	81	146	550	550	524	516	68
46	.....	44	80	133	685	653	636	610	110
24	.....	43	78	144	...	550	539	527	47
25	.....	42	74	145	...	550	530	518	47
32	Pennsylvania No. 19.....	86	96	112	675	541	532	527	41
15	.....	55	85	142	...	456	447	438	27
26	Pennsylvania No. 20.....	44	77	145	...	525	493	484	55
27	.....	52	85	141	...	550	516	508	48
41	Pennsylvania No. 20 W.....	48	84	146	570	594	587	577	56
42	.....	45	76	134	620	388	383	374	53
16	Pennsylvania No. 22.....	48	78	141	...	550	538	520	117
17	.....	63	...	138	...	538	526	515	72
18	.....	47	79	140	...	553	533	503	92
19	.....	46	77	140	...	551	531	504	84
14	.....	47	81	144	...	492	483	459	97
47	Pennsylvania No. 15 (one-half and Rhode Island No. 1 (one- half)).....	45	77	147	665	652	647	616	112
56	Pennsylvania No. 18 (one- fourth) and Miscellaneous No. 9 (three-fourths).....	50	80	126	800	644	637	606	112
57	.....	53	83	125	730	652	645	613	117
35	Pennsylvania No. 18 (one-half and Rhode Island No. 1 (one- half)).....	84	99	102	705	489	482	475	46
49	Pennsylvania No. 18 (three- fourths) and Miscellaneous No. 9 (one-fourth).....	47	79	142	550	648	636	609	130
50	Pennsylvania No. 18 (one-half and Miscellaneous No. 9 (one- half)).....	47	80	140	630	646	638	596	133
51	.....	49	79	139	620	651	643	598	142
7	Virginia No. 5 B.....	37	72	157	...	712	680	639	154
8	.....	45	77	155	...	613	585	549	134

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT ST. LOUIS—(Continued)

Test No.	Designation of Fuel	Proximate Analysis of Fuel as Fired per cent				Ultimate Analysis of Dry Fuel per cent					
		Fixed Carbon	Volatile Matter	Moisture	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash
		26	27	28	29	30	31	32	33	34	35
45	Arkansas No. 13.....	68.30	15.11	1.49	15.10	75.05	3.84	1.81	1.35	2.62	15.38
46	Illinois No. 1.....	41.39	33.15	13.49	11.97	64.88	4.45	10.71	1.03	5.09	13.84
47	Illinois No. 1.....	41.39	33.15	13.49	11.97	64.88	4.45	10.71	1.03	5.09	13.84
48	Illinois No. 7 E.....	40.34	30.09	6.06	23.51	59.48	3.54	5.70	.83	5.42	25.08
39	Illinois No. 9 C.....	47.63	33.55	5.43	13.39	68.44	4.44	8.30	.94	3.72	14.16
13	Illinois No. 12 BW.....	49.47	31.55	7.93	11.05	71.14	4.39	8.90	1.12	2.45	12.00
52	Illinois No. 19 E.....	51.22	31.00	7.33	10.45	.....	.....	.....	.....	2.76	.....
53	.....	51.22	31.00	7.33	10.45	.....	.....	.....	.....	2.76	.....
54	.....	51.22	31.00	7.33	10.45	.....	.....	.....	.....	2.76	.....
55	.....	51.22	31.00	7.33	10.45	.....	.....	.....	.....	2.76	.....
9	Illinois No. 29 A W.....	43.99	37.16	12.29	6.56	72.22	4.92	10.25	1.07	4.06	7.48
12	Illinois No. 29 B.....	44.21	37.44	6.42	11.93	67.10	4.59	10.30	1.00	4.26	12.75
33	Illinois No. 31.....	43.90	33.03	9.17	13.90	66.14	4.33	8.93	1.01	4.29	15.30
34	.....	43.90	33.03	9.17	13.90	66.14	4.33	8.93	1.01	4.29	15.30
44	.....	42.85	35.21	6.98	14.96	66.75	4.85	7.33	.93	4.06	16.08
43	Illinois No. 33.....	40.75	28.25	9.47	21.53	60.07	3.93	9.47	1.03	1.72	23.78
37	Indiana No. 1 B.....	44.78	36.21	4.34	14.67	65.26	4.58	10.84	1.20	2.78	15.94
36	Indiana No. 5 B.....	48.91	35.74	4.20	11.15	70.47	4.85	7.53	.94	4.57	11.64
38	Indiana No. 6 B.....	43.16	37.83	5.72	13.29	66.48	4.76	8.42	1.07	5.17	14.10
10	Indian Territory No. 2 BW.....	54.51	35.86	2.19	7.44	75.69	4.84	8.76	1.53	1.57	7.61
11	Indian Territory No. 2 B.....	51.31	34.60	2.15	11.94	71.96	4.56	8.09	1.45	1.74	12.20
1	Kansas No. 2 B.....	46.78	31.67	2.78	18.77	68.00	4.35	4.90	.96	4.49	19.31
40	.....	47.58	29.09	3.47	19.86	63.78	4.01	5.92	1.03	4.69	20.57
21	Maryland No. 2.....	68.54	21.14	3.63	6.69	82.41	4.74	3.40	1.62	.89	6.94
22	.....	68.54	21.14	3.63	6.69	82.41	4.74	3.40	1.62	.89	6.94
23	.....	68.54	21.14	3.63	6.69	82.41	4.74	3.40	1.62	.89	6.94
20	.....	71.25	18.69	1.69	8.37	.....	.....	.....	.....	.92	.....
2	Missouri No. 10.....	38.67	32.24	11.03	18.06	.....	.....	.....	.....	4.18	.....
3	.....	38.67	32.24	11.03	18.06	.....	.....	.....	.....	4.18	.....
4	.....	38.67	32.24	11.03	18.06	.....	.....	.....	.....	4.18	.....
5	.....	38.67	32.24	11.03	18.06	.....	.....	.....	.....	4.18	.....
28	Pennsylvania No. 18.....	64.61	19.45	7.43	8.51	80.80	4.44	2.88	1.16	1.53	9.19
29	.....	64.61	19.45	7.43	8.51	80.80	4.44	2.88	1.16	1.53	9.19
30	.....	69.14	18.43	4.71	7.72	81.77	4.40	3.22	1.26	1.25	8.10
31	.....	69.14	18.43	4.71	7.72	81.77	4.40	3.22	1.26	1.25	8.10
46	.....	62.80	24.23	2.55	10.42	78.65	4.36	3.38	.88	2.04	10.69
24	.....	71.55	16.71	1.98	9.82	.....	.....	.....	.....	1.91	.....
25	.....	71.88	16.46	3.56	8.10	.....	.....	.....	.....	1.76	.....
32	Pennsylvania No. 19.....	55.24	33.50	1.75	9.51	75.91	4.52	7.16	1.35	1.38	9.68
15	.....	57.20	31.71	2.03	9.06	.....	.....	.....	.....	1.15	.....
26	Pennsylvania No. 20.....	64.38	19.23	6.16	10.23	78.13	4.20	2.83	1.09	2.85	10.90
27	.....	64.38	19.23	6.16	10.23	78.13	4.20	2.83	1.09	2.85	10.90
41	Pennsylvania No. 20 W.....	67.74	20.58	1.23	10.45	79.20	4.56	1.52	1.12	3.02	10.58
42	.....	67.74	20.58	1.23	10.45	79.20	4.56	1.52	1.12	3.02	10.58
16	Pennsylvania No. 22.....	55.12	32.11	2.21	10.56	75.72	4.52	6.41	1.39	1.16	10.80
17	.....	55.12	32.11	2.21	10.56	75.72	4.52	6.41	1.39	1.16	10.80
18	.....	54.27	30.57	3.55	11.61	75.93	4.58	5.10	1.24	1.11	12.04
19	.....	54.27	30.57	3.55	11.61	75.93	4.58	5.10	1.24	1.11	12.04
14	.....	57.96	29.45	1.77	10.82	.....	.....	.....	.....	.90	.....
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half).....	69.71	15.96	.74	13.59	77.47	3.05	2.66	.49	2.64	13.69
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths).....	69.24	15.87	1.06	13.83	76.03	2.81	4.92	.81	1.45	13.98
57	.....	69.24	15.87	1.06	13.83	76.03	2.81	4.92	.81	1.45	13.98
35	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half).....	70.34	16.39	1.34	11.93	77.79	3.46	4.74	.53	1.39	12.09
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth).....	69.52	15.05	1.83	13.60	77.21	3.12	3.48	.70	1.64	13.85
50	Pennsylvania No. 18 (one-half) and Miscellaneous No. 9 (one-half).....	69.67	13.73	1.30	15.30	70.93	2.81	8.80	.75	1.21	15.50
51	.....	69.67	13.73	1.30	15.30	70.93	2.81	8.80	.75	1.21	15.50
7	Virginia No. 5 B.....	65.93	14.28	4.52	15.27	76.18	3.67	2.52	.81	.83	15.99
8	.....	65.93	14.28	4.52	15.27	76.18	3.67	2.52	.81	.83	15.99

TABLE 16 TESTS OF FUEL IN HOUSE HEATING BOILER AT
St. LOUIS—(Continued)

Test No.	Designation of Fuel	Analysis of Ash and Refuse per cent		Fuel per hour pounds				British thermal units per pound of Fuel	
		Carbon	Earthy Matter	As Fired	Dry	Burned per square foot of Grate Surface		Dry	As Fired
						As Fired	Dry		
		37	38	43	43.1	44.1	44	45	46
45	Arkansas No. 13.....	22.06	77.94	93	92	6.99	6.81	13112	12917
58	Illinois No 1	18.40	81.60	108	93	8.00	6.89	12178	10535
59	.....	18.40	81.60	109	95	8.08	7.04	12178	10535
48	Illinois No. 7 E.....	10.02	89.98	121	113	8.96	8.37	10667	10021
39	Illinois No. 9 C.....	15.00	85.00	105	99	7.78	7.33	12385	11713
13	Illinois No. 12 BW.....	23.85	76.15	81	74	6.00	5.48	12958	11930
52	Illinois No. 19 E.....	22.05	77.95	105	97	7.78	7.18	12411	11501
53	.....	22.05	77.95	112	104	8.30	7.70	12411	11501
54	.....	22.05	77.95	101	93	7.48	6.89	12411	11501
55	.....	22.05	77.95	98	90	7.26	6.67	12411	11501
9	Illinois No. 29 AW.....	13.95	86.05	95	84	7.04	6.22	13306	11671
12	Illinois No. 29 B.....	13.56	86.44	102	96	7.56	7.11	12562	11756
33	Illinois No. 31.....	9.47	90.53	104	94	7.70	6.96	12024	10921
34	.....	9.47	90.53	103	94	7.63	6.96	12024	10921
44	.....	11.97	88.03	116	108	8.59	8.00	11995	11158
43	Illinois No. 33.....	26.85	73.15	124	113	9.19	8.38	10782	9761
37	Indiana No. 1 B.....	13.13	86.87	133	127	9.86	9.41	11907	11390
36	Indiana No. 5 B.....	14.79	85.21	110	106	8.15	7.85	12370	12425
38	Indiana No. 6 B.....	10.48	89.52	103	97	7.63	7.18	12557	11839
10	Indian Territory No. 2 BW.....	32.11	67.89	93	91	6.89	6.74	13865	13561
11	Indian Territory No. 2 B.....	15.05	84.95	94	92	6.96	6.82	13196	12912
1	Kansas No. 2 B.....	.....	.....	83	81	6.15	6.00	12132	11795
40	.....	13.53	86.47	97	94	7.18	6.96	11855	11444
21	Maryland No. 2.....	22.64	77.36	82	79	6.08	5.85	14694	14161
22	.....	22.64	77.36	75	71	5.56	5.26	14694	14161
23	.....	22.64	77.36	81	78	6.00	5.78	14694	14161
20	.....	27.30	72.70	66	65	4.89	4.72	14473	14229
2	Missouri No. 10.....	13.89	86.11	151	135	11.20	10.00	11588	10310
3	.....	13.89	86.11	98	87	7.26	6.44	11588	10310
4	.....	13.89	86.11	105	93	7.78	6.89	11588	10310
5	.....	13.89	86.11	127	113	9.41	8.37	11588	10310
28	Pennsylvania No. 18.....	16.64	83.36	73	67	5.41	4.97	14408	13338
29	.....	16.64	83.36	82	76	6.07	5.63	14408	13338
30	.....	12.02	87.98	68	65	5.04	4.81	14559	13873
31	.....	12.02	87.98	69	66	5.11	4.89	14559	13873
46	.....	22.54	77.46	80	78	5.93	5.78	14038	13640
24	.....	25.38	74.62	69	67	5.11	4.97	14096	13820
25	.....	25.38	74.62	69	66	5.11	4.89	14377	13865
32	Pennsylvania No. 19.....	10.44	89.56	82	81	6.08	6.00	13889	13046
15	.....	31.05	68.95	61	60	4.52	4.44	13996	13712
26	Pennsylvania No. 20.....	15.53	84.47	66	62	4.89	4.59	14064	13198
27	.....	15.53	84.47	69	65	5.11	4.82	14064	13198
41	Pennsylvania No. 20 W.....	17.04	82.96	76	75	5.63	5.56	14069	13896
42	.....	17.04	82.96	75	74	5.56	5.48	14069	13896
16	Pennsylvania No. 22.....	15.01	84.99	70	69	5.18	5.11	13677	13561
17	.....	15.01	84.99	67	65	4.96	4.82	13667	13561
18	.....	30.83	69.17	69	67	5.11	4.96	13764	13275
19	.....	30.83	69.17	68	66	5.04	4.89	13764	13275
14	.....	22.96	77.04	65	64	4.82	4.74	13812	13568
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half)	24.55	75.45	79	79	5.85	5.85	12887	12793
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths)	24.20	75.80	79	78	5.85	5.78	12857	12721
57	.....	24.20	75.80	93	92	6.89	6.82	12857	12721
35	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half)	13.89	86.11	86	85	6.37	6.30	13569	13337
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth)	19.30	80.70	79	77	5.85	5.70	13431	13185
50	Pennsylvania No. 18 (one-half) and Miscellaneous No. 9 (one-half)	28.05	71.95	83	81	6.15	6.00	12955	12787
51	.....	28.05	71.95	81	80	6.00	5.92	12955	12787
7	Virginia No. 5 B.....	21.07	75.93	89	85	6.59	6.30	13136	12542
8	.....	24.07	75.93	79	75	5.87	5.56	13136	12542

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT
ST. LOUIS—(Continued)

Test No.	Designation of Fuel	Water pounds		Factor of Evaporation	Equivalent Evaporation per hour from and at 212° F. (pounds)	Horsepower Developed	Equivalent Evaporation per hour from and at 212° F. per sq. ft. of Water Heating Surface (pounds)	Mean Load Carried (sq. ft. of radiating surface)	Percentage of Builders' Rated Capacity Developed
		Fed to Boiler	Evaporated into Dry Steam from and at 212° F.						
45	Arkansas No. 13.....	4186	4487	1.0720	539	15.6	3.39	1797	57.0
58	Illinois No. 1.....	3422	3754	1.0970	474	13.7	2.98	1580	50.2
59	.....	3809	4159	1.0919	520	15.1	3.27	1733	55.0
48	Illinois No. 7 E.....	3708	3989	1.0759	499	14.5	3.14	1663	52.8
39	Illinois No. 9 C.....	3786	4089	1.0800	493	14.3	3.10	1643	52.2
13	Illinois No. 12 B W.....	3188	3430	1.0758	416	12.1	2.62	1387	44.0
52	Illinois No. 19 E.....	3625	3914	1.0798	502	14.6	3.16	1673	53.1
53	.....	4482	4886	1.0902	592	17.2	3.73	19.3	62.6
54	.....	3325	3599	1.0825	447	13.0	2.81	1490	47.3
55	.....	3959	4334	1.0946	554	16.1	3.49	1847	58.7
9	Illinois No. 29 A W.....	4900	5239	1.0692	665	19.3	4.18	2217	70.4
12	Illinois No. 29 B.....	4134	4423	1.0700	615	17.8	3.87	2050	65.1
33	Illinois No. 31.....	3960	4407	1.1130	563	16.3	3.54	1877	59.6
34	.....	4292	4801	1.1187	594	17.2	3.74	1960	62.9
44	.....	4248	4585	1.0794	550	15.9	3.46	1833	58.2
43	Illinois No. 33.....	3805	4075	1.0710	521	15.1	3.28	1737	55.2
37	Indiana No. 1 B.....	4915	5399	1.0985	648	18.8	4.08	2160	68.6
36	Indiana No. 5 B.....	4523	5048	1.1161	600	17.4	3.77	2000	63.5
38	Indiana No. 6 B.....	3962	4272	1.0782	542	15.7	3.41	1807	57.4
10	Indian Territory No. 2 B W.....	4866	5198	1.0682	656	19.0	4.13	2187	69.4
11	Indian Territory No. 2 B.....	5411	5739	1.0606	729	21.1	4.58	2430	77.2
1	Kansas No. 2 B.....	3433	3686	1.0737	461	13.4	2.90	1537	48.8
40	.....	4023	4357	1.0829	528	15.3	3.32	1760	55.9
21	Maryland No. 2.....	4895	5224	1.0673	653	18.9	4.11	2177	69.1
22	.....	4188	4489	1.0719	599	17.4	3.77	1997	63.4
23	.....	4260	4581	1.0754	573	16.6	3.60	1910	60.6
20	.....	4079	4377	1.0731	556	16.1	3.50	1853	58.8
2	Missouri No. 10.....	5152	5498	1.0671	718	20.8	4.52	2393	76.0
3	.....	3824	4087	1.0688	522	15.1	3.28	1740	55.2
4	.....	4036	4356	1.0792	557	16.1	3.50	1857	59.0
5	.....	5415	5755	1.0627	708	20.5	4.45	2360	74.9
28	Pennsylvania No. 18.....	3720	4014	1.0790	502	14.6	3.16	1673	53.1
29	.....	4879	5246	1.0752	656	19.0	4.13	2187	69.4
30	.....	4404	4722	1.0723	613	17.8	3.86	2043	64.9
31	.....	4095	4393	1.0728	549	15.9	3.45	1830	58.1
46	.....	4343	4710	1.0845	579	16.8	3.64	1930	61.3
24	.....	4209	4520	1.0740	565	16.4	3.55	1883	59.8
25	.....	4113	4413	1.0729	552	16.0	3.47	1840	58.4
32	Pennsylvania No. 19.....	3142	3450	1.1076	529	15.3	3.33	1763	56.0
15	.....	3239	3487	1.0765	465	13.5	2.92	1550	49.2
26	Pennsylvania No. 20.....	4069	4367	1.0733	546	15.8	3.43	1820	57.8
27	.....	3829	4126	1.0775	516	15.0	3.25	1720	54.6
41	Pennsylvania No. 20 W.....	4416	4735	1.0723	606	17.6	3.81	2020	64.2
42	.....	2703	2931	1.0844	564	16.3	3.55	1880	59.7
16	Pennsylvania No. 22.....	3473	3743	1.0776	478	13.9	3.01	1593	50.6
17	.....	3531	3816	1.0807	472	13.7	2.97	1573	49.9
18	.....	3457	3723	1.0769	465	13.5	2.92	1550	49.2
19	.....	3627	3909	1.0777	486	14.1	3.06	1620	51.4
14	.....	3844	4132	1.0748	545	15.8	3.43	1817	57.7
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half).....	3993	4273	1.0700	519	15.0	3.26	1730	54.9
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths).....	4173	4555	1.0915	558	16.2	3.51	1860	59.1
57	.....	3698	4042	1.0929	577	16.7	3.63	1923	61.0
35	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half).....	3118	3485	1.1177	616	17.9	3.87	2053	65.2
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth).....	4308	4636	1.0761	563	16.3	3.54	1877	59.6
50	Pennsylvania No. 18 (one-half) and Miscellaneous No. 9 (one-half).....	3860	4158	1.0773	531	15.4	3.34	1770	56.2
51	.....	3928	4237	1.0787	530	15.4	3.33	1767	56.1
7	Virginia No. 5 B.....	5353	5678	1.0608	710	20.6	4.47	2367	75.1
8	.....	4270	4544	1.0642	583	16.9	3.67	1943	61.6

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT ST. LOUIS—(Continued)

Test No.	Designation of Fuel	Economic Results pounds				Efficiency per cent	
		Equivalent Evap- oration from and at 212° F. per pound of Fuel		Fuel per hour per 100 square feet of Radiating Sur- face (mean load carried during test)		Boiler and Furnace (dry fuel basis)	Plant (fuel as fired basis)
		As Fired	Dry	As Fired	Dry		
		57	58	59	60	61	62
45	Arkansas No. 13.....	5.77	6.14	5.18	5.12	45.22	43.14
58	Illinois No. 1.....	4.40	5.32	6.84	5.89	42.19	40.33
59	.....	4.76	5.71	6.29	5.48	45.28	43.63
48	Illinois No. 7 E.....	4.13	4.56	7.28	6.80	41.28	39.80
39	Illinois No. 9 C.....	4.69	5.18	6.39	6.02	40.39	38.67
13	Illinois No. 12 BW.....	5.15	5.84	5.84	5.34	43.52	41.69
52	Illinois No. 19 E.....	4.79	5.39	6.28	5.80	41.94	40.22
53	.....	5.27	5.91	5.68	5.27	45.99	44.25
54	.....	4.44	4.97	6.78	6.24	38.67	37.28
55	.....	5.67	6.33	5.30	4.87	49.25	47.61
9	Illinois No. 29 AW.....	6.98	8.08	4.29	3.79	58.64	57.75
12	Illinois No. 29 B.....	6.02	6.59	4.98	4.68	50.66	49.45
33	Illinois No. 31.....	5.42	6.08	5.54	5.00	48.83	47.93
44	.....	5.74	6.46	5.20	4.75	51.88	50.76
43	.....	4.74	5.21	6.33	5.89	41.94	41.02
37	Illinois No. 33.....	4.19	5.36	7.14	6.50	48.01	41.45
36	Indiana No. 1 B.....	4.89	5.21	6.16	5.88	42.25	41.46
38	Indiana No. 5 B.....	5.44	5.82	5.50	5.30	43.33	42.28
10	Indiana No. 6 B.....	5.24	5.70	5.70	5.37	43.84	42.74
38	Indian Territory No. 2 BW.....	7.06	7.58	4.25	4.16	52.79	50.28
11	Indian Territory No. 2 B.....	7.79	8.20	3.87	3.79	60.01	58.26
1	Kansas No. 2 B.....	5.53	5.69	5.40	5.27	45.29	45.28
40	.....	5.45	5.86	5.51	5.34	47.74	45.99
21	Maryland No. 2.....	8.02	8.54	3.77	3.63	56.13	54.69
22	.....	8.02	8.41	3.76	3.55	55.27	54.69
23	.....	7.05	7.50	4.24	4.08	49.29	48.08
20	.....	8.42	8.72	3.56	3.51	58.18	57.15
2	Missouri No. 10.....	4.75	5.58	6.31	5.64	46.50	44.49
3	.....	5.31	6.28	5.63	5.00	52.34	49.74
4	.....	5.32	6.27	5.66	5.01	52.25	49.83
5	.....	5.55	6.41	5.58	4.79	53.42	51.98
28	Pennsylvania No. 18.....	6.92	7.56	4.37	4.01	50.67	50.10
29	.....	8.05	8.78	3.75	3.48	58.85	58.28
30	.....	9.00	9.52	3.33	3.18	63.15	62.65
31	.....	7.99	8.52	3.77	3.61	56.51	55.62
46	.....	7.21	7.72	4.14	4.04	52.71	50.90
24	.....	8.22	8.58	3.67	3.56	58.78	57.44
25	.....	8.02	8.52	3.75	3.59	57.25	55.86
32	Pennsylvania No. 19.....	6.43	6.60	4.65	4.60	45.89	45.50
15	.....	7.64	7.96	3.94	3.87	54.92	53.81
26	Pennsylvania No. 20.....	8.32	9.02	3.63	3.41	61.94	60.88
27	.....	7.50	8.12	4.01	3.78	55.76	54.88
41	Pennsylvania No. 20 W.....	7.97	8.21	3.76	3.71	56.35	55.39
42	.....	7.56	7.84	3.99	3.94	53.81	52.54
16	Pennsylvania No. 22.....	6.81	7.20	4.40	4.33	50.14	48.50
17	.....	7.10	7.41	4.26	4.13	51.60	50.56
18	.....	6.74	7.41	4.45	4.32	51.99	49.03
19	.....	7.09	7.76	4.20	4.07	54.45	51.58
14	.....	8.40	9.00	3.58	3.52	62.93	59.79
47	Pennsylvania No. 15 (one-half and Rhode Island No. 1 (one- half).....	6.55	6.94	4.57	4.57	52.01	49.44
56	Pennsylvania No. 18 (one- fourth) and Miscellaneous No. 9 (three-fourths).....	7.08	7.52	4.25	4.19	56.48	53.75
57	.....	6.20	6.60	4.84	4.79	49.57	47.07
35	Pennsylvania No. 18 (one-half and Rhode Island No. 1 (one- half).....	7.13	7.34	4.19	4.14	52.24	51.43
49	Pennsylvania No. 18 (three- fourths) and Miscellaneous No. 9 (one-fourth).....	7.16	7.61	4.21	4.10	54.72	52.44
50	Pennsylvania No. 18 (one-half and Miscellaneous No. 9 (one- half).....	6.44	6.98	4.69	4.57	52.03	48.64
51	.....	6.51	7.09	4.59	4.53	52.85	49.16
7	Virginia No. 5 B.....	7.98	8.89	3.76	3.59	65.36	61.44
8	.....	7.42	8.28	4.07	3.86	60.87	57.13

TABLE 16 TESTS OF FUEL IN HOUSE-HEATING BOILER AT
ST. LOUIS—(Concluded).

Test No.	Designation of Fuel	Fuel at \$1 per 2000 pounds		Thickness of Fire inches	Average Amount of Fuel Fired at each Firing pounds	Average Interval Between Firings hours	Clinkers in Refuse per cent	Black Smoke per cent
		Cost in cents per 100 square feet of Radiating Surface per hour (mean load carried during test)	Cost (in cents) of Evaporating 1000 pounds of Water from and at 212° F.					
		64	65	69	70	71		77
45	Arkansas No. 13.....	0.2590	8.67	8-16	155	1.66	15	30.3
58	Illinois No. 1	.3420	11.36	8-14	171	1.58	38	25.7
59	.....	.3150	10.50	8-16	175	1.60	38	41.2
48	Illinois No. 7 E.....	.3640	12.10	.....	161	1.33	19	40.3
39	Illinois No. 9 C.....	.3200	10.65	.....	145	1.36	28	32.6
13	Illinois No. 12 BW	.2420	9.71	.....	74	.92	0	24.1
52	Illinois No. 19 E.....	.3140	10.44	4-12	163	1.56	0	37.1
53	.....	.2840	9.49	8-16	155	1.37	20	30.3
54	.....	.3390	11.25	8-16	162	1.61	21	32.5
55	.....	.2650	8.82	6-14	153	1.56	0	31.5
9	Illinois No. 29 A W.....	.2150	7.16	.....	62	.66	0	19.2
12	Illinois No. 29 B.....	.2490	8.31	.....	67	.65	26	34.6
33	Illinois No. 31.....	.2770	9.23	.....	163	1.56	13	22.7
34	.....	.2600	8.71	.....	167	1.61	24	23.7
44	.....	.3170	10.55	8-16	161	1.39	46	29.1
43	Illinois No. 33.....	.2570	11.93	6-18	162	1.30	14	32.8
37	Indiana No. 1 B.....	.3080	10.22	4-16	158	1.19	48	28.5
36	Indiana No. 5 B.....	.2750	9.19	4-14	155	1.40	34	32.2
38	Indiana No. 6 B.....	.2850	9.54	8-14	163	1.58	47	32.3
10	Indian Territory No. 2 BW	.2130	7.08	.....	74	.79	0	30.4
11	Indian Territory No. 2 B.....	.1940	6.42	.....	67	.71	0	25.2
1	Kansas No. 2 B.....	.2700	9.04	.....	56	.66	44	22.6
40	.....	.2760	9.18	6-18	160	1.65	33	26.4
21	Maryland No. 2.....	.1890	6.24	.....	93	1.14	0	14.4
22	.....	.1880	6.24	.....	140	1.32	0	.....
23	.....	.2120	7.09	.....	163	2.00	0	10.7
20	.....	.1780	5.94	.....	65	.98	0	1.4
2	Missouri No. 10.....	.3160	10.52	.....	116	.77	29	41.6
3	.....	.2820	9.42	.....	55	.56	38	51.4
4	.....	.2830	9.40	.....	55	.52	29	30.6
5	.....	.2690	9.01	.....	65	.51	30	41.1
28	Pennsylvania No. 18.....	.2190	7.23	.....	145	2.00	0	12.7
29	.....	.1880	6.21	.....	163	2.00	0	14.2
30	.....	.1670	5.56	.....	131	1.92	0	25.5
31	.....	.1890	6.26	4-12	138	2.00	0	36.8
46	.....	.2070	6.94	.....	163	2.03	20	26.7
24	.....	.1840	6.08	.....	138	2.00	0	7.2
25	.....	.1880	6.24	.....	138	2.00	0	9.2
32	Pennsylvania No. 19.....	.2350	7.78	.....	135	1.64	0	45.7
15	.....	.1970	6.54	.....	41	.68	0	14.2
26	Pennsylvania No. 20.....	.1820	6.01	.....	131	2.00	0	16.6
27	.....	.2010	6.67	.....	138	2.00	0	17.7
41	Pennsylvania No. 20 W.....	.1880	6.27	4-16	148	1.96	0	29.7
42	.....	.2000	6.61	6-18	129	1.73	0	.....
16	Pennsylvania No. 22.....	.2200	7.34	.....	61	.87	0	25.1
17	.....	.2130	7.04	.....	60	.89	0	26.7
18	.....	.2230	7.42	.....	69	1.00	0	33.3
19	.....	.2100	7.05	.....	138	2.01	0	22.9
14	.....	.1790	5.96	.....	62	.95	0	16.1
47	Pennsylvania No. 15 (one-half) and Rhode Island No. 1 (one-half).....	.2290	7.64	4-18	163	2.06	24	29.9
56	Pennsylvania No. 18 (one-fourth) and Miscellaneous No. 9 (three-fourths).....	.2130	7.06	8-18	161	2.04	24	32.2
57	Pennsylvania No. 18 (one-half) and Rhode Island No. 1 (one-half).....	.2420	8.06	8-16	163	1.75	25	31.4
35	.....	.2100	7.01	4-12	162	1.88	0	19.3
49	Pennsylvania No. 18 (three-fourths) and Miscellaneous No. 9 (one-fourth).....	.2110	6.98	.....	162	2.06	16	.....
50	Pennsylvania No. 18 (one-half) and Miscellaneous No. 9 (one-half).....	.2350	7.77	8-16	162	1.96	0	28.9
51	.....	.2300	7.68	10-18	163	2.00	0	32.6
7	Virginia No. 5 B.....	.1880	6.27	.....	65	.73	0	16.7
8	.....	.2040	6.74	.....	123	1.56	0	39.5

TABLE 17
AVERAGE PERCENTAGE OF CO₂, O₂, AND CO
FROM 52 TESTS MADE ON FUEL IN HOUSE-
HEATING BOILER AT ST. LOUIS

Test No.	CO ₂	O ₂	CO	Test No.	CO ₂	O ₂	CO
7	10.1	6.35	0.40	34	7.2	10.9	0.1
8	10.9	5.4	1.02	35	7.8	9.80	.10
9	10.22	7.56	.7	36	7.9	8.3	.96
10	9.74	8.44	.34	37	12.1	4.3	.75
11	7.57	10.0	.68	38	9.3	6.8	.55
12	9.26	8.30	.44	39	8.75	5.45	1.0
13	6.96	11.35	.20	40	8.2	8.86	.53
14	7.0	10.68	.52	41	6.7	10.8	.20
15	5.8	11.30	.18	42	7.1	9.8	.25
16	6.8	11.3	.56	43	6.8	11.4	.4
17	6.8	10.26	.43	44	7.6	9.4	.4
18	7.2	9.85	.65	45	13.3	4.3	.6
19	8.0	8.77	.84	46	10.3	6.75	.65
20	7.13	9.83	.53	47	9.2	9.25	.15
21	8.6	7.25	.51	48	8.3	9.8	.6
22	8.0	6.58	1.62	49	8.1	9.80	.60
23	7.5	7.40	1.28	50	8.6	9.3	.15
24	6.8	11.84	.24	51	9.4	9.0	.60
25	7.0	11.60	.11	52	8.75	7.65	1.50
26	7.6	10.35	.28	53	9.8	6.65	1.0
27	5.8	12.81	.05	54	9.7	6.5	.6
28	7.5	10.75	.46	55	12.5	4.0	.75
29	7.4	10.76	.34	56	9.8	7.10	.40
30	7.4	10.63	.13	57	9.9	7.90	.25
31	6.5	10.40	.30	58	9.3	8.1	.45
32	7.0	10.35	.15	59	9.7	7.4	1.2

APPENDIX C

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE
ENGINEERING EXPERIMENT STATION UNIVERSITY OF
ILLINOIS*

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Shape of Briquets	Date	Duration of Test hours	Average Pressure				Average Temperature (°F.)			
						Steam gage		Draft (in. of water)		External Air	Boiler Room	Feed Water in Weigh Tank	
						Boiler	Receiver	Flue	Over Fire				
				1907	1	10	11	12	13	14	15	16	
136	D1	Illinois No. 7 E.....	Round..	June 19.	8.62	4.25	1.87	0.15	0.10	..	..	148.9	
137	D2	.. ..	.. ..	.. ..	7.38	4.98	1.58	.16	.06	..	..	158.0	
152	D1	Illinois No. 9 C.....	.. ..	June 28.	7.78	6.39	2.02	.15	.12	74	79	164.5	
153	D2	.. ..	.. ..	.. ..	8.02	5.04	1.71	.15	.06	74	79	168.3	
154	D1	Illinois N W.....	.. ..	June 29.	7.97	7.04	2.06	.15	.12	82	83	159.9	
155	D2	.. ..	.. ..	.. ..	7.50	3.60	1.32	.13	.03	82	83	161.6	
142	D1	Illinois No. 31.....	.. ..	June 22.	7.35	6.69	2.05	.15	.11	..	..	151.3	
143	D2	.. ..	.. ..	.. ..	6.85	5.22	1.67	.15	.05	..	..	153.7	
144	D1	.. ..	Square..	June 24.	7.93	5.61	1.94	.17	.10	..	..	150.8	
145	D2	.. ..	.. ..	.. ..	7.52	6.02	1.70	.22	.04	..	..	144.5	
158	D1	Illinois No. 33.....	Round..	July 2.	7.97	6.78	2.05	.15	.12	75	81	165.1	
159	D2	.. ..	.. ..	.. ..	8.15	5.34	1.71	.18	.05	75	81	166.0	
140	D1	Indiana No. 1 B.....	.. ..	June 21.	7.97	6.12	2.08	.15	.12	..	..	152.3	
141	D2	.. ..	.. ..	.. ..	7.47	5.30	1.68	.18	.04	..	..	157.0	
146	D1	Indiana No. 6 B.....	.. ..	June 25.	8.05	6.32	1.97	.15	.11	78	82	169.1	
147	D2	.. ..	.. ..	.. ..	8.00	3.76	1.46	.19	.02	78	82	173.4	
148	D1	.. ..	Square..	June 26.	8.08	6.59	2.07	.17	.13	77	83	155.8	
149	D2	.. ..	.. ..	.. ..	8.25	5.44	1.74	.17	.05	77	83	156.6	
138	D1	Missouri No. 10.....	Round..	June 20.	7.95	5.68	1.97	.14	.10	..	..	163.1	
139	D2	.. ..	.. ..	.. ..	7.67	4.44	1.86	.20	.05	..	..	162.7	
156	D1	Pennsylvania No. 20 W..	.. ..	July 1.	9.17	6.11	2.00	.14	.12	83	88	167.2	
157	D2	.. ..	.. ..	.. ..	8.02	5.40	1.60	.14	.07	83	88	169.7	
150	D1	Pennsylvania No. 22.	Square..	June 27.	8.13	5.72	2.02	.18	.14	74	79	157.5	
151	D2	.. ..	.. ..	.. ..	8.45	6.09	1.86	.15	.06	74	79	165.4	

*See "21. Data and Results," p. 63.

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF
ILLINOIS—(Continued)
Tests on Briquets

Test No.	Boiler	Designation of Fuel	Fuel as Fired (pounds)				Dry Fuel (pounds)			Total Ash and Refuse from Ash Pit (pounds)	Residual Fuel Removed (pounds)
			Wood	Briquets	Briquets plus Wood	Corrected for residual Fuel	Total Fired	Corrected for Residual Fuel	Actually Consumed (Corrected for Carbon in Ash)		
			20	21	21.1	21.2	23	23.1	23.2	24	25
136	D1	Illinois No. 7 E.....	6.0	372	374.4	340.5	347.9	316.4	307.4	34.0	82.5
137	D2	.....	6.2	335	337.5	318.9	313.6	296.3	272.8	76.0	34.0
152	D1	Illinois No. 9 C.....	10.0	275	279.0	266.2	259.8	247.8	245.2	26.0	27.0
153	D2	.....	10.0	375	379.0	363.0	352.9	338.0	325.8	51.0	23.5
154	D1	Illinois No. 30 W.....	10.0	255	259.0	251.1	242.6	235.2	233.9	13.0	14.2
155	D2	.....	10.0	300	304.0	280.5	284.7	262.7	256.9	23.0	27.7
142	D1	Illinois No. 31.....	6.0	265	267.4	253.9	241.9	229.7	224.0	27.0	24.0
143	D2	.....	10.0	275	279.0	269.3	252.4	243.6	232.6	45.0	14.0
144	D1	.....	7.5	275	278.0	267.8	254.5	245.2	236.1	35.5	16.0
145	D2	.....	7.2	300	302.9	288.9	277.3	264.4	249.7	42.5	20.5
158	D1	Illinois No. 33.....	10.0	260	264.0	254.6	247.5	238.6	235.8	24.0	19.0
159	D2	.....	10.5	340	344.2	326.8	322.7	306.3	301.4	34.5	26.5
140	D1	Indiana No. 1 B.....	10.0	275	279.0	268.7	260.0	250.4	240.6	32.5	16.0
141	D2	.....	10.0	300	304.0	291.8	283.3	271.9	261.4	43.0	15.5
146	D1	Indiana No. 6 B.....	10.0	265	269.0	261.4	255.3	248.1	244.2	23.0	17.5
147	D2	.....	10.0	340	344.0	318.6	326.5	302.4	297.2	33.5	33.0
148	D1	.....	10.0	265	269.0	253.2	255.8	240.8	238.8	21.0	31.5
149	D2	.....	10.0	340	344.0	326.3	327.1	310.3	303.5	38.5	26.5
138	D1	Missouri No. 10.....	6.0	300	302.4	282.5	282.6	264.0	247.5	57.0	27.0
139	D2	.....	6.0	375	377.4	360.2	352.6	338.5	322.7	62.5	32.0
156	D1	Pennsylvania No. 20W	10.0	225	229.0	214.6	221.8	207.8	202.7	17.2	16.0
157	D2	.....	11.0	225	229.4	217.4	225.2	210.6	201.9	22.0	14.7
150	D1	Pennsylvania No. 22..	10.0	225	229.0	209.2	220.7	201.6	196.7	20.0	24.0
151	D2	.....	10.0	226	280.0	252.5	269.9	243.4	236.0	25.0	38.0

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT
ENGINEERING EXPERIMENT STATION UNIVERSITY
OF ILLINOIS—(Continued)

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Proximate Analysis of Fuel as Fired per cent				Ash in Ultimate Analysis of Dry Fuel (per cent)	Residual Fuel per cent	
			Fixed Carbon	Volatile Matter	Moisture	Ash		Carbon	Earthy Matter
			26	27	28	29	35	37	38
136	D ₁	Illinois No. 7 E.....			7.07	.....	27.43	26.50	73.50
137	D ₂	".....			7.07	.....	27.43	35.34	64.66
152	D ₁	Illinois No. 9 C.....			6.89	.....	14.69	35.87	64.13
153	D ₂	".....			6.89	.....	14.69	51.44	48.56
154	D ₁	Illinois No. 30 W.....			6.34	.....	8.35	46.47	53.53
155	D ₂	".....			6.34	.....	8.35	71.34	28.66
142	D ₁	Illinois No. 31.....			9.53	.....	16.81	40.71	59.29
143	D ₂	".....			9.53	.....	16.81	50.39	49.61
144	D ₁	".....			8.46	.....	16.76	46.16	53.84
145	D ₂	".....			8.46	.....	16.76	49.72	50.28
158	D ₁	Illinois No. 33.....			6.26	.....	13.67	40.06	59.94
159	D ₂	".....			6.26	.....	13.67	53.09	46.91
140	D ₁	Indiana No. 1 B.....			6.80	.....	14.11	50.81	49.19
141	D ₂	".....			6.80	.....	14.11	62.24	37.76
146	D ₁	Indiana No. 6 B.....			5.08	.....	12.27	35.80	64.20
147	D ₂	".....			5.08	.....	12.27	63.04	36.96
148	D ₁	".....			4.91	.....	13.51	40.29	59.71
149	D ₂	".....			4.91	.....	13.51	53.58	46.42
138	D ₁	Missouri No. 10.....			6.56	.....	21.57	51.85	48.15
139	D ₂	".....			6.56	.....	21.57	37.98	62.02
156	D ₁	Pennsylvania No. 20 W.....			3.16	.....	7.98	85.21	14.79
157	D ₂	".....			3.16	.....	7.98	76.78	23.22
150	D ₁	Pennsylvania No. 22.....			3.61	.....	9.68	74.34	25.66
151	D ₂	".....			3.61	.....	9.68	65.23	34.77

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE
ENGINEERING EXPERIMENT STATION UNIVERSITY OF
ILLINOIS—(Continued)

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Ash (per cent)		Dry Fuel per hour (pounds)		British thermal units per pound of Fuel		Moisture in Steam (per cent)
			Carbon	Earthy Matter	Total	Per square foot of Grate Surface	Dry	As Fired	
136	D1	Illinois No. 7 E	18.30	81.70	36.72	8.58	10142	9425	1.02
137	D2	"	21.47	78.53	40.13	6.69	10142	9425	.61
152	D1	Illinois No. 9 C	8.23	91.77	31.84	7.43	11845	11029	.99
153	D2	"	19.44	80.56	42.16	7.03	11845	11029	.90
154	D1	Illinois No. 30 W	9.32	90.68	29.52	6.90	13134	12301	.82
155	D2	"	22.77	77.23	35.03	5.84	13134	12301	1.11
142	D1	Illinois No. 31	17.01	82.99	31.25	7.30	11685	10571	.83
143	D2	"	19.50	80.50	35.56	5.93	11685	10571	.66
144	D1	"	20.30	79.70	30.90	7.22	11574	10595	1.09
145	D2	"	27.41	72.59	35.17	5.86	11574	10595	.72
158	D1	Illinois No. 33	10.26	89.74	29.95	7.00	12573	11786	.95
159	D2	"	12.38	87.62	37.58	6.26	12573	11786	.89
140	D1	Indiana No. 1 B	25.57	74.43	31.43	7.34	12379	11537	.85
141	D2	"	20.85	79.15	36.42	6.07	12379	11537	.69
146	D1	Indiana No. 6 B	14.58	85.42	30.82	7.20	12617	11976	.90
147	D2	"	13.47	86.53	37.81	6.30	12617	11976	.93
148	D1	"	7.87	12.13	29.78	6.96	12319	11714	.76
149	D2	"	14.94	85.06	37.61	6.27	12319	11714	.81
138	D1	Missouri No. 10	21.87	78.13	33.21	7.76	11012	10290	.93
139	D2	"	16.64	83.36	43.89	7.32	11012	10290	.65
156	D1	Pennsylvania No. 20 W	28.87	71.13	22.67	5.30	14262	13811	.98
157	D2	"	38.61	61.39	26.26	4.38	14262	13811	.78
150	D1	Pennsylvania No. 22	23.17	76.83	24.79	5.79	13646	13153	1.08
151	D2	"	27.70	72.30	28.80	4.80	13646	13153	.80

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF
ILLINOIS--(Continued)
Tests on Briquets

Test No.	Boiler	Designation of Fuel	Factor for Correction, Quality of Steam	Water pounds			Factor of Evaporation	Water per hour pounds		Horse-power Developed
			Fed to Boiler	Corrected for Quality of Steam	Evaporated into Dry Steam from and at 212° F.	Equivalent Evaporation from and at 212° F.		Equivalent Evaporation from and at 212° F. per square foot of Water-heating Surface		
									48		49	50	52	51	53	54
136	D1	Illinois No. 7 E.....	0.9905	1292	1280	1366	1.0677	158.5	3.63	4.59
137	D2	".....	.9943	1386	1377	1457	1.0580	197.3	2.69	5.72
152	D1	Illinois No. 9 C.....	.9907	1215	1204	1266	1.0517	162.7	3.72	4.72
153	D2	".....	.9914	1589	1575	1650	1.0477	205.8	2.80	5.97
154	D1	Illinois No. 30 W.....	.9923	1302	1292	1365	1.0566	171.3	3.92	4.97
155	D2	".....	.9895	1234	1221	1287	1.0542	171.6	2.34	4.97
142	D1	Illinois No. 31.....	.9923	1147	1138	1212	1.0655	165.0	3.78	4.78
143	D2	".....	.9938	1346	1337	1421	1.0626	207.5	2.83	6.01
144	D1	".....	.9900	1228	1216	1296	1.0660	163.5	3.74	4.74
145	D2	".....	.9933	1457	1447	1552	1.0722	206.7	2.82	5.99
158	D1	Illinois No. 33.....	.9910	1270	1259	1323	1.0512	166.0	3.80	4.81
159	D2	".....	.9916	1515	1502	1577	1.0497	193.5	2.64	5.61
140	D1	Indiana No. 1 B.....	.9920	1216	1206	1285	1.0650	161.3	3.69	4.68
141	D2	".....	.9935	1281	1273	1350	1.0592	180.7	2.47	5.24
146	D1	Indiana No. 6 B.....	.9914	1270	1259	1320	1.0469	164.0	3.75	4.76
147	D2	".....	.9911	1420	1407	1466	1.0420	183.3	2.50	5.31
148	D1	".....	.9929	1299	1289	1368	1.0609	169.2	3.87	4.91
149	D2	".....	.9923	1669	1655	1754	1.0598	212.5	2.90	6.16
138	D1	Missouri No. 10.....	.9912	1243	1232	1297	1.0532	163.2	3.74	4.73
139	D2	".....	.9939	1557	1546	1630	1.0534	212.5	2.90	6.16
156	D1	Pennsylvania No. 20 W.....	.9907	1377	1364	1431	1.0489	156.1	3.57	4.53
157	D2	".....	.9926	1555	1543	1614	1.0460	201.3	2.74	5.84
150	D1	Pennsylvania No. 22.....	.9899	1264	1251	1325	1.0590	163.0	3.73	4.73
151	D2	".....	.9924	1689	1676	1761	1.0506	208.4	2.84	6.04

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE
ENGINEERING EXPERIMENT STATION UNIVERSITY OF

ILLINOIS—(Continued)

Tests on Briquets

Test No.	Boiler	Designation of Fuel	Mean Load Carried		Percentage of Builder's Rated Capacity Developed (per cent)	Economic Results (pounds)			
			Square Feet Radiating Surface	Square Feet of Radiating Surface plus Radiating Surface of Boiler		Equivalent Evaporation from and at 212° F. per pound of Fuel		Fuel per hour per 100 square feet of radiating Surface (mean load carried during test)	
						Fuel as Fired	Dry Fuel Consumed	As Fired	Dry
			55	55.1	56	57	58	59	60
136	D1	Illinois No. 7 E.....	528	566	66.0	4.01	4.44	7.48	6.95
137	D2	"	658	761	61.2	4.57	5.34	6.57	6.10
152	D1	Illinois No. 9 C.....	542	580	67.8	4.76	5.16	6.31	5.87
153	D2	"	686	789	63.8	4.55	5.06	6.60	6.15
154	D1	Illinois No. 30 W.....	571	609	71.4	5.44	5.84	5.52	5.17
155	D2	"	572	675	53.2	4.59	5.01	6.54	6.12
142	D1	Illinois No. 31.....	550	588	68.8	4.77	5.41	6.28	5.68
143	D2	"	692	795	64.3	5.28	6.11	5.68	5.14
144	D1	"	545	583	68.2	4.84	5.49	6.19	5.67
145	D2	"	689	792	64.1	5.37	6.22	5.58	5.10
158	D1	Illinois No. 33.....	553	591	69.2	5.20	5.61	5.77	5.41
159	D2	"	645	748	60.0	4.83	5.23	6.22	5.83
140	D1	Indiana No. 1 B.....	538	576	67.2	4.78	5.34	6.27	5.85
141	D2	"	602	706	56.0	4.63	5.16	6.49	6.05
146	D1	Indiana No. 6 B.....	547	585	68.3	5.05	5.41	5.94	5.64
147	D2	"	611	714	56.8	4.60	4.93	6.52	6.19
148	D1	"	564	602	70.5	5.40	5.73	5.55	5.28
149	D2	"	708	812	65.8	5.38	5.78	5.58	5.31
138	D1	Missouri No. 10.....	544	582	68.0	4.59	5.24	6.53	6.10
139	D2	"	708	812	65.9	4.53	5.05	6.63	6.20
156	D1	Pennsylvania No. 20 W.....	520	558	65.0	6.67	7.06	4.50	4.36
157	D2	"	671	774	62.4	7.42	7.99	4.04	3.91
150	D1	Pennsylvania No. 22.....	543	581	67.9	6.33	6.74	4.73	4.56
151	D2	"	695	798	64.6	6.97	7.46	4.30	4.15

TABLE 18

TESTS OF FUEL IN HOUSE-HEATING BOILERS MADE AT THE
ENGINEERING EXPERIMENT STATION, UNIVERSITY OF
ILLINOIS—(Concluded)
Tests on Briquets

Test No.	Boiler	Designation of Fuel	Efficiency per cent		Cost (in cents) per 100 sq. ft. of Radiating Surface per hour (mean load carried during test) <i>a</i>	Cost (in cents) of Evaporating 1,000 lb. of Water from and at 212° F. <i>a</i>	Average Amount of Fuel Fired at each Firing (pounds)	Average Interval hours		Maximum Interval of Maintaining 2 lb. or more Steam Pressure without Attention (hours)
			Boiler and Furnace	Plant				Between Firings	Between Times of Shaking and Raking	
			61	62	64	65	70	71	72	73
136	D1	Illinois No. 7 E.....	42.28	41.09	0.374	12.47	75	1.53	1.02	2.00
137	D2	.....	50.85	46.83	.374	10.94	45	1.04	.76	1.77
152	D1	Illinois No. 9 C.....	42.07	41.69	.328	10.50	75	2.13	2.13	2.22
153	D2	.....	41.26	39.84	.316	10.99	75	1.76	1.77	2.22
154	D1	Illinois No. 30 W.....	42.94	42.71	.330	9.19	75	2.40	2.40	2.55
155	D2	.....	36.84	36.04	.276	10.89	75	1.74	1.74	2.37
142	D1	Illinois No. 31.....	44.72	43.58	.327	10.48	75	2.31	2.31	2.38
143	D2	.....	50.50	48.24	.314	9.47	75	2.13	2.13	2.73
144	D1	.....	45.81	44.12	.284	10.33	75	2.52	2.52	2.60
145	D2	.....	51.90	48.95	.310	9.31	75	2.01	2.01	2.25
158	D1	Illinois No. 33.....	43.09	42.61	.279	9.62	75	2.61	2.61	2.83
159	D2	.....	40.17	39.58	.289	10.35	75	1.91	1.91	2.62
140	D1	Indiana No. 1 B.....	41.66	40.02	.311	10.46	75	2.21	2.21	2.22
141	D2	.....	40.26	38.76	.314	10.80	75	1.94	1.94	2.05
146	D1	Indiana No. 6 B.....	41.41	40.73	.325	9.90	75	2.54	2.54	3.03
147	D2	.....	37.74	37.10	.297	10.87	75	1.89	1.89	2.48
148	D1	.....	44.92	44.52	.326	9.26	75	2.73	2.81	3.62
149	D2	.....	45.31	44.36	.278	9.29	75	2.14	2.14	1.83
138	D1	Missouri No. 10.....	45.96	43.08	.279	10.89	75	1.91	1.91	2.00
139	D2	.....	44.29	42.52	.327	11.04	75	1.42	1.46	1.67
156	D1	Pennsylvania No. 20 W.....	47.81	46.64	.332	7.50	75	3.25	3.25	3.60
157	D1	.....	54.11	51.89	.225	6.74	75	3.12	3.13	3.35
150	D1	Pennsylvania No. 22.....	47.70	46.48	.232	7.90	75	3.44	3.44	3.68
151	D2		52.80	51.18	.215	7.17	75	2.51	2.52	2.17

a Based on fuel as \$1 per 2000 lb.

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- Bulletin* No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print*).
- Circular* No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905. (*Out of print*).
- Bulletin* No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. (*Out of print*).
- Circular* No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906. (*Out of print*).
- Circular* No. 3. Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907, by L. P. Breckenridge and Paul Diserens. 1909.
- Bulletin* No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (*Out of print*).
- Bulletin* No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.
- Bulletin* No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906. (*Out of print*).
- Bulletin* No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906. (*Out of print*).
- Bulletin* No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906. (*Out of print*).
- Bulletin* No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906. (*Out of print*).
- Bulletin* No. 9. An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.
- Bulletin* No. 10. Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print*).
- Bulletin* No. 11. The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907. (*Out of print*).
- Bulletin* No. 12. Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print*).
- Bulletin* No. 13. An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.
- Bulletin* No. 14. Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print*).
- Bulletin* No. 15. How to Burn Illinois Coal without Smoke, by L. P. Breckenridge. 1908.
- Bulletin* No. 16. A Study of Roof Trusses, by N. Clifford Ricker. 1908.
- Bulletin* No. 17. The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1908. (*Out of print*).
- Bulletin* No. 18. The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1908.
- Bulletin* No. 19. Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908. (*Out of print*).
- Bulletin* No. 20. Tests of Concrete and Reinforced Concrete Columns, Series of 1907, by Arthur N. Talbot. 1908. (*Out of print*).
- Bulletin* No. 21. Tests of a Liquid Air Plant, by C. S. Hudson and C. M. Garland. 1908.
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- Bulletin* No. 29. Tests of Reinforced Concrete Beams: Resistance to Web Stresses, by Arthur N. Talbot. 1909.
- Bulletin* No. 30. On the Rate of Formation of Carbon Monoxide in Gas Producers, by J. K. Clement, L. H. Adams, and C. N. Haskins. 1909.
- Bulletin* No. 31. Fuel Tests with House-heating Boilers, by J. M. Snodgrass. 1909.

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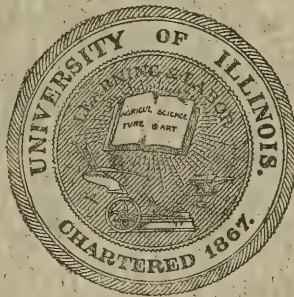
THE OCCLUDED GASES IN COAL

BY

S. W. PARR

AND

PERRY BARKER



UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 32

MARCH 1909

THE OCCLUDED GASES IN COAL

By S. W. PARR, PROFESSOR OF APPLIED CHEMISTRY

AND

PERRY BARKER, RESEARCH ASSISTANT IN THE DIVISION OF APPLIED
CHEMISTRY

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I. INTRODUCTION

Experimental studies on coal have been carried on for some time in the Laboratory of Industrial Chemistry at the University of Illinois. A number of topics have been taken up, such as Weathering,¹ Distillation at Low Temperature,² Pure Coal,³ Classification,⁴ The Composition and Analysis of Illinois Coal,⁵ etc., etc.

These studies, while conducted as independent lines of work, are so interrelated that not infrequently the facts brought out under one division have aided very materially in the interpretation of results obtained under another heading. Especially, also, has it been found that each one of the original topics has subdivided so that the main subjects have grown in number. This is well illustrated in our studies on the weathering of coal. As the facts accumulated in that work, it very soon became evident that an initial loss of heat values occurred in the first few days after release of the coal from the seam, which could not be credited to oxidizing conditions. This naturally led to the study of the topic which we have for convenience designated the Deterioration of Coal, because it is not strictly a weathering process. A preliminary report on this phase was made in Bulletin No. 17 of the Engineering Experiment Station. Additional information on this topic was also published in an article contributed to the Journal of the American Chemical Society,⁶ showing conclusively the fact that a positive exudation of combustible gases occurs in freshly mined coal. From the development of this fact there naturally arose the necessity of inaugurating an independent series of experiments which has resulted in this special study of the occluded gases in coal.

Another subdivision of the work on weathering naturally arose in connection with the storage of coal. For a complete understanding of all phases of this topic it seemed essential that we add to our information concerning the causes underlying spontaneous combustion. As a means for promoting this latter end it was thought that a study of the occluded gases, their composition,

¹ Bulletin No. 17, Univ. of Ill. Eng. Exp. Sta.

² Bulletin No. 24, Univ. of Ill. Eng. Exp. Sta.

³ Trans. Am. Inst. Min. Engrs., July, 1907.

⁴ Jour. Am. Chem. Soc. Vol. 28, p. 1425.

⁵ University Studies, Vol. 1, No. 7.

⁶ Jour. Am. Chem. Soc., Vol. 30, p. 1027.

behavior, interreactions, etc., would contribute much needed information upon this very important point. Some of the results presented herewith bear upon this topic in quite an unexpected manner, and particular attention is called in the accompanying tables to the marked avidity of coal for oxygen.

Again, it is an interesting fact to note that in the studies as outlined in Bulletin No. 24 on the low temperature distillation of coal, a subdivision of that topic came about as a natural result of certain experiments which indicated an unexpectedly low temperature at which active oxidation was effected. A detailed study was therefore made of oxidation conditions, the temperatures at which chemical action was set up, and the relation between the external temperature and the speed of such reactions.¹ The fact was soon developed that oxidation took place at much lower temperatures than had been supposed. It is very evident, therefore, from a simple statement of these facts that we have developed still another independent topic as a result of the study of oxidation temperatures on one hand and the experiments connected with the occluded gases on the other. This work has, therefore, been taken up under the heading of Spontaneous Combustion. Here, it will be noted, the behavior of the occluded gases plays an important part, and it was believed that the facts which might develop from such a study would contribute materially to our understanding of oxidation in this more active form. Already the results of this line are beginning to give promise of information which will be of special value, and will at least contribute to a better understanding of this difficulty, if indeed there will not develop practical suggestions as to methods for avoiding the danger and loss attending the firing of coal in storage. It is hoped that this work will be sufficiently advanced to warrant at least a preliminary report during the current year.

Concerning the work here outlined on the occluded gases, it should be said that the study is not to be considered by any means complete. The facts obtained make a well rounded unit, as a preliminary study, and since a considerable time must elapse before the final round of work can be completed, it has seemed advisable to publish the results that have been thus far worked out with much skill and patience by Mr. Barker.

¹ Bulletin No. 24, Univ. of Ill. Eng. Exp. Sta.

Provision has been made by the Engineering Experiment Station for again taking up this work.

Thanks are due also to Dr. H. Foster Bain, Director of the Illinois State Geological Survey, for cooperation in this and the other investigations on Illinois coal. It is directly due to assistance from these two sources that the coal studies carried on in this laboratory have been made possible.

II. BIBLIOGRAPHY

All varieties of coal, as well as peat, are known to contain occluded or mechanically enclosed gases. Their nature and amount are dependent upon the structure and age of the coal and the conditions of weathering to which it has been exposed. A large part of these gases escapes when the coal is first exposed in the seam. At times the immense volume and explosive or poisonous nature of the escaping nitrogen, carbon dioxide, and methane derivatives, make it either dangerous or impossible to mine the coal. However, a portion is retained within the coal only to be given up by continued exposure and at increased temperatures.

Within the past thirty years numerous investigations of the character of the gases occluded in European coals have been made. The first investigation of this sort was conducted by Websky¹, who made an examination of the gases evolved by peat.

He found this gas to consist of nitrogen, 53.67; carbon dioxide, 2.97; and methane, 43.36. Later, Von Meyer² made quite an extensive examination of various German coals. The method of extraction in these experiments was as follows. The coal in nut-sized pieces was placed in a flask and covered with freshly boiled water. The flask was securely stoppered with a rubber cork, having an outlet to a bell for collecting the gas. On heating, the gas enclosed in the coal was given off and replaced a corresponding volume of water in the collector. The first series of experiments was upon Zwickan coal, both in the fresh state and after exposure, as shown in Table I.

¹ Jour. prakt. Chemie., Vol. 92, p. 76, (1864).

² Jour. prakt. Chemie., Vol. 5, p. 144, (1872).

Abs. Jour. Chem. Soc. Vol. 10, p. 798, (1872)

TABLE I
GASES IN ZWICKAN COAL

I, III, and V, coal fresh from seam.
 II same as I, weathered for 5 years.
 IV " " III, " " 1½ years.
 VI " " V, " " 5 years.

	I Fresh	II Weathered	III Fresh	IV Weathered	V Fresh	VI Weathered
Vol. per 100 g.	38.00	18.20	25.50	18.60	52.80	13.60
CO ₂	2.42%	16.70%	4.02%	2.25%	.60%	7.62%
O	2.51	4.90	.62	.70	.0	2.44
C ₂ H ₄		1.47				.96
CH ₄	71.90	3.17	45.00	73.16	51.40	15.88
C ₂ H ₆		18.61				22.35
N	23.17	55.15	50.36	23.89	48.00	50.75

A series of coal from Bochum, both fresh and weathered, was also examined, with results as shown in Table II.

TABLE II
GASES IN BOCHUM COAL

	I Fresh	II Weathered	III Fresh	IV Weathered	V Fresh	VI Weathered
Vol. per 100 g.	50.6	43.2	43.3	41.2	59.2	43.6
CO ₂	4.87%	11.12%	2.18%	15.84	4.82%	7.68%
O	2.66	2.88	2.12	3.06	1.99	2.24
CH ₄	16.65	7.40	25.19	6.57	31.57	3.31
N	75.82	78.60	70.51	74.53	60.62	86.77

	VII Fresh	VIII Weathered	IX Fresh	X Weathered	XI Fresh	XII Weathered
Vol. per 100 g.	54.4	39.2	54.5	39.6	42.0	36.4
CO ₂	1.30%	4.35%	2.02%	2.15%	3.72%	8.49%
O	1.60	3.35	.90	3.14	.39	3.57
CH ₄	30.25	11.12	10.65	3.43	5.70	.0
N	66.85	81.18	86.43	91.28	90.19	87.94

The author notes the increase in the ratio of nitrogen content over that of ordinary air. He maintains that the nitrogen has been enclosed in the coal during its formation, that a part results

from the reactions in the formation, and that another part is due to the air taken into the material of the coal, this last portion being the residue from the air, the oxygen having been absorbed by the coal with the formation of water and CO_2 . He refers to the recent study upon the oxidation of coal by Richter,¹ who maintains that the resulting compound is principally water, while only comparatively small amounts of CO_2 were formed. This theory seems to be borne out by the above analyses in which the CO_2 has never completely replaced the oxygen of the air. It is also noted that one of these coals, very high in sulphur, gave high CO_2 , which is in accordance with Richter's² statement, that increase in the content of pyrite, facilitates the absorption of oxygen. The presence of higher hydrocarbons of the methane series, also ethylene, indicates a possible rise in temperature within the coal during exposure, due to the absorption of oxygen with a resulting destructive distillation.

Later, this same author³ has investigated a number of English coals. He found in none of these any gases absorbable by fuming sulphuric acid, and methane was the predominating combustible gas. O. Kolbe,⁴ in the same year, reported several analyses of lignites. Von Meyer has also made a second series of investigations on German coals.⁵

In 1875 Thomas⁶ began extensive tests upon the gases occluded in English coals. He devised an entirely different method for removing the gases. The coal was placed, in one large piece, in a glass tube which was sealed to a Sprengel mercury pump. When a vacuum had been established, the tube containing the coals was immersed in water at 100°C ., and the gases removed by the pump. The rapidity of evolution of the gas depends upon the hardness of the coal and the quantity contained. The following table gives the results of Thomas's first series of experiments.

¹ Chem. Centralblatt, 1870, p. 245, 543.

² Chem. Centralblatt, 1870, p. 543.

³ Jour. prakt. Chemie., Vol. 6, p. 407, (1872).

Abs. Jour. Chem. Soc., Vol. 10, p. 801.

⁴ Jour. prakt. Chemie., Vol. 6, p. 79, (1873).

⁵ Jour. prakt. Chemie., Vol. 6, p. 389, (1873).

⁶ Jour. Chem. Soc., Vol. 13, p. 793, (1875).

TABLE III
GASES IN ENGLISH COALS

		Cc. per 100 grams	CO ₂	O	CH ₄	N
1	Bituminous	55.9	36.42%	.80%	.00%	62.78%
2	"	61.2	16.77	2.72	.40	80.11
3	"	55.1	5.44	1.05	63.76	29.75
4	Semi-bituminous	73.6	12.34	.64	72.51	14.51
5	Steam coal	194.8	5.04	.33	87.30	7.33
6	"	250.1	13.21	.49	81.64	4.66
7	"	218.4	5.46	.44	84.22	9.88
8	"	147.4	18.90	1.02	67.47	12.61
9	"	375.4	9.25	.34	86.92	3.49
10	"	149.3	11.35	.56	73.47	14.62
11	"	215.4	5.64	.54	82.70	11.12
12	"	24.0	22.16	6.09	2.68	69.07
13	"	39.7	9.43	2.25	31.98	56.34
14	"	555.5	2.62		93.13	4.25
15	"	600.6	14.72		84.18	1.10

The second series of analyses of Thomas was on the gases evolved from fans or "blower gas". Some previous work¹ has been done upon this class of gases and Thomas's work confirmed these results. Most of these samples contained between 94 and 97 per cent of methane.

In another publication Thomas² gives the results of the examination of samples of lignites. He concludes, as in the case of a previous author,³ that lignites oxidize readily and always contain a small percentage of CO.

¹ Bischof, Edinburgh New Phil. Jour, Vol, 29, p. 39. Vol. 30. p. 127, (1840).

Bunsen, Petersburg Akad. Bull, Vol. 14, p. 59.

Playfair, Memoirs of the Chemical Soc., Vol. 2, p. 7.

Graham, Memoirs Geol. Sur. Gt. Britain, Vol. 1, p. 460.

² Jour. Chem. Soc., Vol. 17, p. 146, (1877).

³ Varretropp, Chem. Centralblatt, 1865, p. 953.

TABLE IV
GASES PRESENT IN LIGNITES

I Bohemian lignite III Bovey Heathfield lignite (at 100° C.)
II Earthy lignite IV Mineral resin

	I	II	III	IV
Vol. per 100 g.	-----	-----	59.9	21.4
CO ₂	96.41%	83.99%	89.53%	88.24%
O	.32	.65	-----	.23
CO	1.20	1.04	5.11	7.90
CH ₄	trace	-----	.33	.47
N	2.17 ₁	14.91	5.03	3.16

¹ Adds to 100.10 per cent in the original manuscript.

A series of experiments by Thomas on cannel coals and jets was reported² in the same year.

TABLE V
ANALYSES OF CONTAINED GASES IN CANNEL COALS AND JET

I Wigan cannel coal IV Scotch cannel coal
II " " " V Whitehill cannel shale
III Scotch " " VI Whitby jet

	I	II	III	IV	V	VI
Vol. per 100 g.	42.13	35.06	16.80	55.70	55.70	30.20
CO ₂	6.44%	9.05%	53.94%	84.55%	68.75%	10.93%
CH ₄	80.69	77.19				
C ₂ H ₆	4.75	7.80			2.67	
C ₄ H ₁₀				.91*		86.90
N	8.12	5.96	46.06	14.54	28.58	2.17

* C₃H₈

The noticeable feature in the gases extracted from these cannel coals is the high percentages of C₂H₆ and the absence of oxygen.

Bedson³ has reported the first analyses upon the gases extracted from coal dusts and found that they showed a general resemblance to those removed from coal and that all the combus-

² Jour. Chem. Soc., Vol. 15, p. 144, (1876).

³ Trans. North of Eng. Inst. Min. & Mech. Eng., Vol. 37, p. 245, (1888).

Abs. Jour. Soc. Chem. Ind., Vol. 7, p. 729, (1888).

tible constituents consisted of olefiant gases and methane derivatives.

Several years later Bedson¹ published results of amounts of gas given off when coals were heated to 100°C. for 100 hours. Fine coal gave about 300 cu. ft. of gas per ton and of this gas one-sixth was CH₄. Upon reducing these samples further to dust, more gas (20 cu. ft. per ton) was given off, of which 18 per cent was CH₄.

McConnell² investigated several seams of English coals as to their content of enclosed gases. Particular attention was paid to the nature of the paraffin hydrocarbons extracted from these coals. One of these analyses from a mine where an explosion had recently taken place showed CO₂, 1.7, 0, 1.0; methane, 88.7; nitrogen, 8.7. The author concludes that the deeper seams yield coals containing combustible gas and CO₂ while the younger ones contain more CO₂ and less combustible gases.

Broockmann³ criticizes the results of Bedson and McConnell, saying that explosions of dust are not dependent upon the gaseous content of the same. He also states that rubber stoppers will not stand a vacuum, thereby diluting the gas with the products of reactions at high temperatures between the air that has leaked in and the coal.

Bedson⁴ has replied to Broockmann's criticism and maintains that his apparatus was air-tight, as all rubber joints were coated with a vacuum-proof cement. He also states that the Austrian Fire-damp Commission has corroborated his statements in regard to the relation of enclosed gases to the inflammable nature of dusts. The author notes the absorption of oxygen by samples exposed in the laboratory, and in this way accounts for the high oxygen-nitrogen ratio in some of his samples.

The latest experimental work upon gases occluded in coal has been conducted by Trowbridge,⁵ who compared the gases in fresh coal, "mother of coal", surface dust, and dust from timbers. He concludes that his data show the absorption of gases from the

¹Jour. Soc. Chem. Ind. Vol. 11, p. 832, (1892).

²Jour. Soc. Chem. Ind. Vol. 13, p. 25, (1894).

³Trans. North of Eng. Inst. Min. & Mech. Eng. Vol. 52, p. 16, (1902).

Abs. Jour. Soc. Chem. Ind., Vol. 22, p. 86, (1903).

⁴Trans. North of Eng. Inst. Min. & Mech. Eng., Vol. 52, p. 25, (1902).

Abs. Jour. Soc. Chem. Ind., Vol. 22, p. 86, (1903).

⁵Jour. Soc. Chem. Ind., Vol. 25, p. 1129, (1906).

air, preferably oxygen. Two analyses of fresh and exposed coal are given.

	Fresh	Exposed
CO ₂	1.65%	1.18%
O	8.79	23.80
CH ₄	44.60	3.58
N	44.76	71.44

Clark¹ upon summing up most of the data upon this subject comments upon the inability to make any comparisons of the results at hand, as all samples represented some loss in transit from mine to laboratory. Of course this loss is dependent upon the structure of the coal and upon the time occupied in transit.

In view of the fundamental relation it bears to a fuller understanding of the subject of alterations in coal, whether in transit or storage, this study of the composition, behavior, and reactions of the occluded gases has been undertaken.

III. SCOPE OF EXPERIMENTAL WORK

The experimental work may be conveniently described under the following headings:

1. The construction of apparatus for evacuating the samples.
2. The construction of apparatus for exact gas analysis.
3. The construction of apparatus for collecting samples and devising methods for making collections of coal and the occluded gases.
4. The analysis of the last portion of air and enclosed gases in several samples of coal that had been exposed outside for periods varying from two to fifteen months.
5. The analysis of the last portion of air and the enclosed gases in four sections of a vertical core cut from a pile of screenings that had been exposed outside for fifteen months.
6. The analysis of the gas that had surrounded samples kept in jars for a year; these samples had been previously kept sealed tight for one year, then were transferred to separate jars.
7. The analysis of gas that surrounded samples that had been sealed as soon as they came from the mine.

¹Bull. U. S. Geol. Surv., No. 330, p. 660.

8. The analysis of the last portion of air and the enclosed gases from a set of samples of drillings sealed at the mines.

9. The analysis of the last portion of air and the enclosed gases from a set of face mine samples that had been stored in the laboratory for two years. This set of samples corresponded as to mine location with the set described in (8).

10. Miscellaneous analyses of gases from samples used for experiments upon the absorption of oxygen by coal.

IV. DESCRIPTION AND MANIPULATION OF APPARATUS

The apparatus used for the removal of the occluded gases from the samples of coal consisted of a modified form of the Boltwood mercury air pump, as used by Cady and McFarland¹ in the determination of helium in natural gas, and is shown in Fig. 1. *A* is a side neck funnel for holding mercury. *B* is a stopcock to regulate the feed of the mercury flowing from *A* through *C* and producing a vacuum through *G*, *H*, etc. *D* is a 300 cc. bell jar supplied with a stopcock and is used to collect the gases brought down through *C* by the mercury column. *E* is the outlet of the tube for the return lift for the mercury. *L* is the overflow hole in the mercury tank *M* and keeps *E* from becoming sealed during the operation of the pump. *F* is the return lift to the reservoir *A*, which is connected to an ordinary filter pump through *K*. *G* is a drying U-tube of alternate lengths of phosphorus pentoxide (P_2O_5) and glass wool having ground glass joints to *C* and *H*, the latter being a drying tower of calcium chloride. At *I*, the outlet tube to *H*, a wide end is made in the tubing to admit the constricted tips of the coal sample containers of which *J* is a representation. This joint at *I* is made with rubber resin (Khotinsky) cement.² In operating the pump the stopcock *N* is closed and *O* is opened so that the train *G* and *H* can be completely evacuated before any gas from the coal container is admitted. Mercury is allowed to flow from *A* through *C* and out into *M*, the amount being regulated at the cock *B*. While the train is being evacuated, *D* is left empty with the stopcock open or is removed altogether. As *M* fills, the suction at *K* draws mercury from the surface at *E* and returns it to the reservoir *A*. Should the mercury come through *C* too fast,

¹ Jour. Amer. Chem. Soc., Vol. 29, p. 1523, (1907).

² Jour. Amer. Chem. Soc., Vol. 30, p. 20, (1908).

a seal will be formed at *E*. To prevent this an overflow is provided at *L*, and *E* is so regulated that it is on a level with the lowest point of *L*. In order to further prevent a stoppage at *E*, the mouth of this tube was filled with fine iron wire at first, but later a constriction was made at the bend *U* and this kept too much

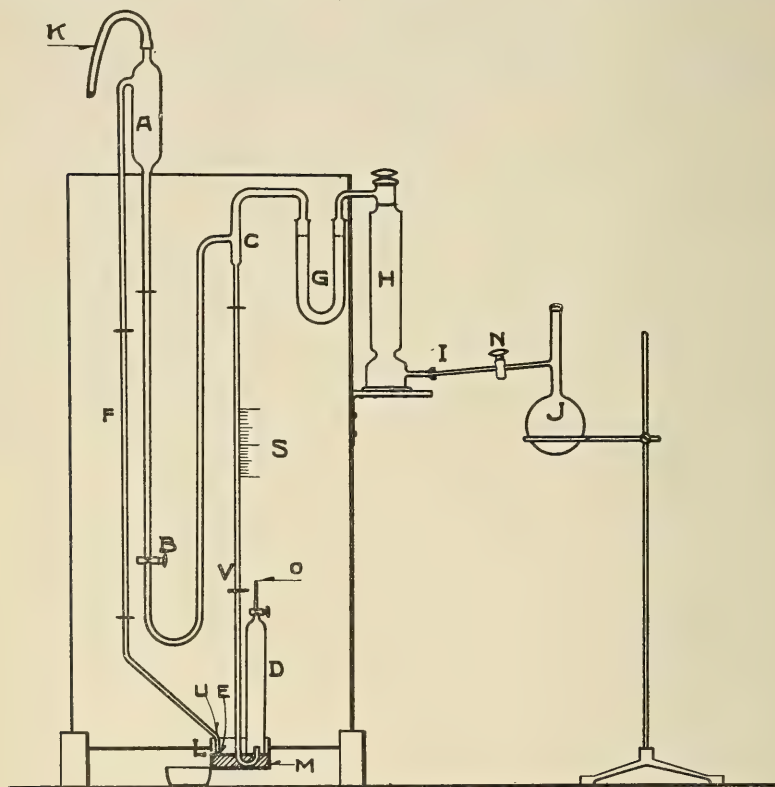


FIG. 1

mercury from passing up at a time. When a vacuum had been produced in the train, a solid column remained in *V* and after shutting off the pump connected to *K*, the column *V* should read within 1 or 2 millimeters of barometric height. The scale *S* facilitated the taking of barometer readings, as it was graduated in millimeters above the outlet into the tank *M*. The bell jar *D* is now filled with mercury by pouring into *M* and applying the filter pump to the outlet of *D* at *O*. After completely filling the

holder *D* the mercury pump is again started and *N* is opened to allow the gas from *J* to be removed. As this gas comes down *V*, it collects and displaces mercury in *D*. When the column shows approximately barometric height on *S*, the pump is stopped and the gases are transferred from *D* and analyzed.

The apparatus used for gas analysis consisted of a regular set of Hempel's pipettes using an explosion pipette for hydrocarbons. All volumes of gas were measured by means of the Hempel¹ compensating burette shown in Fig. 2. The arrangement and operation of this burette are described by Hempel as follows:

"The instrument consists of the graduated measuring tube *A*, the correction tube *B*, the manometer tube *F*, and the level bulb *G*. The measuring tube and leveling bulb are mounted in suitable iron feet. The measuring tube and the correction tube stand in the wide glass cylinders *C*, which are filled with water to insure that these two tubes are at all times at the same temperature.....

"The correction tube *B* and the manometer tube *F* are made from simple glass tubes fused together in the form shown in the cut; *g* is a small capillary tube. The manometer tube is U-shaped, and is somewhat widened at *k* and *i*, these two widened portions having marks scratched on the glass at exactly the same height. The manometer tube is joined to the measuring tube by means of a piece of rubber tubing connecting the end of the capillary *l* with the tube *a* of the stopcock. The reason for making the manometer tube so long lies in the fact that otherwise, if the apparatus is carelessly handled, the mercury might easily be driven from the manometer tube into the burette or the correction tube. With the arrangement shown in the figure this is almost impossible, since the difference in pressure must be more than half an atmosphere before the mercury can pass over into either tube.....

"Before proceeding with the analysis, the volume of the manometer tube from the mark *k* to the point *a* must be ascertained. To do this, draw over the mercury in the manometer until it reaches *a*, then turn the stopcock *D* to connect with the capillary *b*, and now draw any desired volume of air into the burette. Leaving the stopcock open, read off this volume of air on the scale of the burette, the air here being, of course, under the pre-

¹ Hempel,—Dennis, Gas Analysis, 3rd Edition, p. 60.

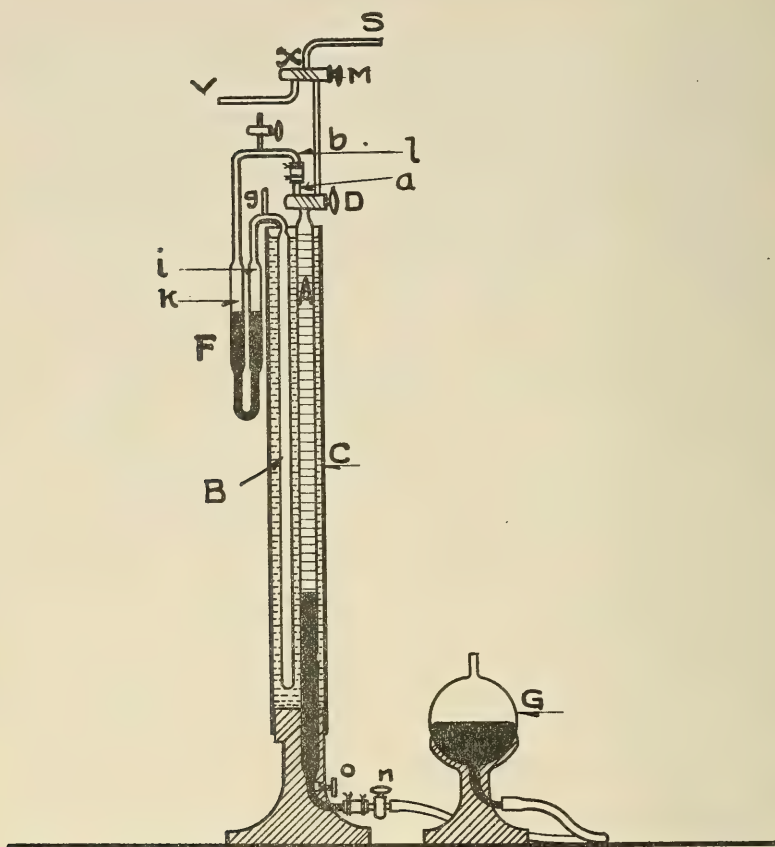


FIG. 2

vailing pressure of the atmosphere. Turn stopcock *D* so that the burette communicates with the manometer tube, and drive the air over into this latter tube until the mercury in it stands at equal height in its two branches; that is, at the marks on *k* and *i*. The difference between the two readings on the measuring tube, provided the tube *g* remains open, gives the volume of the manometer from the mark on *k* up to *a*.....

"In many cases it is highly desirable to arrange the apparatus so that the reading on the measuring tube *A* corresponds directly to volumes at 0° C. and 760 mm. pressure. To accomplish this, a piece of rubber tubing is slipped over the end of the capillary tube *g* and fastened firmly in place by a wire ligature. By

lowering the level-bulb, mercury is drawn over into the manometer tube until it reaches the capillary *l*, and the burette is then allowed to stand for two hours in a room of fairly constant temperature. The stopcock *D* is then opened so that the contents of the burette are in free communication with the atmospheric air. As soon as one is convinced that all parts of the apparatus are at the same temperature, the gas volume in the burette is read exactly, and the temperature and barometric pressure are noted. The thermometer and barometer should stand in the same room with the apparatus. The stopcock *D* is closed and the volume which the gas would occupy at 0° C. and 760 mm. barometric pressure is now calculated.

Example: The gas volume is 97 ccm., the barometric pressure 753.3 mm. and the temperature 8.75° C. The space from *k* to *a* in the manometer has previously been determined and found to be 1.8 ccm. The tension of the water vapor at 8.75° C. is 8.4 mm.

"If *b* represents the observed barometric pressure, *t* the temperature, *e* the tension of water vapor at that temperature, and *V* the observed volume, the volume *V*₀ which the gas would occupy under standard conditions may be calculated from the following formula:—

$$V_0 = V \frac{b - e}{760 (1 + 0.00367 t)}$$

In the above example this volume is 92.1 ccm.

Since, however, in making measurements with the correction tube, the gas fills the space from *k* to *a*, this volume must be subtracted from the above results:—

$$92.1 - 1.8 = 90.3 \text{ ccm.}$$

"In order now to adjust the gas volume in the correction tube so that readings of volumes in the burette will be reduced at once to standard conditions, the stopcock *D* is turned so that the burette communicates with the manometer tube, and the gas volume in the burette is compressed by raising the level-bulb *G* to the volume which it has been calculated that it would occupy at 0° C. and 760 mm. pressure. The mercury in the manometer tube is, of course, forced out of equilibrium by this operation. Air is now blown into the correction tube through the rubber tube at *g* until the mercury stands at the same height in the two branches

of the manometer tube, and the rubber tube is then closed by means of a strong pinchcock placed directly above the end of *g*."

In reading the volumes of gas in the burette, the mercury was always drawn over to *a* and left there while an absorption was being made. The extra stopcock *M* does away with any correction for the connection capillary tube *S*. Whatever absorbent is to be used is driven up from the pipette through *S* to *x*. *M* is then turned so that it connects with *b*, the gas being driven through *S* into the pipette. On returning, the absorbent is brought up to *x* and *M* and *D* are closed. The level at *k* and *i* is established and the volume read. To all readings the volume from *k* to *a* must be added to get the total gas in the burette. *M* is now turned so that the solution in *S* can be washed out through *Y* and the next absorbing pipette is attached.

The containers for samples consisted of the flasks such as *J*, Fig. 1, Putman fruit jars and Mason fruit jars. All the samples for removal of enclosed gases were placed in flasks (*J*). These were 300 cc. fractionating flasks with a stopcock at the outlet. As soon as the sample was placed in this flask, the stopcock was closed and a rubber stopper coated with the Khotinsky cement was sealed in at the mouth. The stopcocks on all the apparatus used in this were lubricated with a special mixture of 16 parts of vaseline, 1 part of paraffin, and 8 parts of pure rubber, maintained at a temperature of 350 to 400° for several hours.¹ The Putnam jars² were used for all samples from which the surrounding gas was to be removed by displacement. These were inverted and opened in a tank of water, saturated with CO₂ and illuminating gas, and all gas contained therein was removed by inserting a tube at the mouth and pulling the gas into a holder over mercury. The Mason jars were used for submerged samples. To remove the gas that adhered to the coal under water, the tops were removed and, as the gas was dislodged upon agitating the jars, it was collected in a bell jar, inverted over the top of the container.

V. EXPERIMENTAL DATA

The first set of experiments in connection with the study of the occluded gases in Illinois coal consisted of the examination of

¹ Jour. Amer. Chem. Soc. Vol. 29, p. 1725.

² Univ. of Ill. Eng. Exp. Sta. Bull. 17, p. 34.

a vertical section from a pile of $1\frac{1}{2}$ inch screenings that had been exposed outside for 5 months. At the time of collection, this pile had been smoldering for two months. Five days before taking the samples it had been wetted down. A core 7 in. in diameter and about 85 in. long was cut vertically from the pile by means of the cylindrical sampler. As the sampler went through the pile it was removed after going down 20 in., and the contents were, in each case, sampled separately. The samples were transferred at once to flasks, as shown by *J*, Fig. 1, and left in contact with the enclosed air for varying lengths of time as shown in the tables. The analyses of the different sections are given in Table VI.

TABLE VI
GASES IN COAL FROM SMOLDERING SCREENINGS

I Christian County screenings First 20 inches of pile	III Christian County screenings Third 20 inches of pile
II Christian County screenings Second 20 inches of pile	IV Christian County screenings Fourth 20 inches of pile

Part 1 Last Portion of Air

	I	II	III	IV
Time of Standing, days	2	1	1	1
Weight of Coal, grams	200	200	200	200
Vol. of Gas at 0° C. 760 mm.	56.9	59.2	65.2	79.9
Cc. of Gas per 100 grams	28.45	29.6	32.6	38.95
CO ₂	.7	.7	3.2	3.15
O	5.6	6.1	4.0	7.60
CH ₄	.25	.05	0.	0.
N	21.90	22.75	25.4	28.20
Per cent by Volume				
CO ₂	2.46	2.37	9.32	7.90
O	19.69	20.61	12.27	19.02
CH ₄	.90	.17	0.	0.
N	76.95	76.85	78.41	73.08

Part 2 Gas Removed by Vacuum

Time of Standing, days	7	8	9	8
Weight of Coal, grams	200	200	200	200
Vol. of Gas at 0° C. 760 mm.	3.2	17.6	36.6	8.0
Cc. of Gas per 100 grams	1.6	8.8	18.3	4.0
CO ₂	.5	2.2	4.05	1.85
O	0.	1.05	1.45	.45
CH ₄	.1	.15	.75	.2
N	1.0	5.40	12.05	1.50
Per cent by Volume				
CO ₂	31.25	25.0	22.13	46.25
O	0.	11.93	7.93	11.25
CH ₄	6.25	1.70	4.10	5.00
N	62.50	61.37	65.84	37.50

TABLE VII

COMPOSITION OF GAS EXUDED FROM FRESH COAL

- I Lebanon, Lebanon City Coal Co., sealed, dry.
 II Lebanon, Lebanon City Coal Co., sealed, submerged.
 III Bennett, Bennett Mine, International Coal Mining Co., sealed, dry.
 IV Bennett, Bennett Mine, International Coal Mining Co., sealed, submerged.
 V O'Fallon, Mine No. 2, St. Louis & O'Fallon Coal Co., sealed, dry.
 VI O'Fallon, Mine No. 2, St. Louis & O'Fallon Coal Co., sealed, submerged.

	I Dry	II Submerged	III Dry	IV Submerged	V Dry	VI Submerged
Weight of Coal, grams	642	800	648	800	787	800
Volume of Gas cc. (a)	446(b)	38.8	442(b)	29.3	331(b)	97.8
Per cent by Volume						
CO ₂	0.	0.	5.88	0.	.88	0.
O	18.50	1.87	7.64	1.03	0.	1.08
CH ₄	0.	55.97	0.	35.39	11.83	90.28
N	81.50	42.16	86.48	63.58	87.29	8.64

(a) At normal temperature and pressure.

(b) Total gas from containers.

In order to study the composition of the gas found in certain experiments¹ to be liberated from Illinois coal and shown also to be combustible, several samples were collected from fresh seam

¹ Jour. Am. Chem. Soc., Vol. 30, p. 1027.

faces and allowed to stand for seven months. They were then opened under water and the gas surrounding the coal in the containers was collected by displacement. A similar set of samples was collected in jars which were filled with water and whatever gas had been given off at the end of seven months was collected. The results of these two sets of analyses are given in Table VII.

It is evident that aside from the addition of methane and carbon dioxide to the ordinary constituents of air, a decrease in the percentage of oxygen originally contained in the air of the jars has taken place. In order to test the extent of this absorption of oxygen, a number of samples of coal were placed in jars with large volumes of air equal to about six to ten times the several volumes of coal. After being in contact with the coal for a year the air was collected by displacement and analyzed. The following results show the general nature of the changes which had taken place, Table VIII.

TABLE VIII

THE ABSORPTION OF OXYGEN BY COAL

- I Springfield, Sangamon Mine, Sangamon Coal Co.
- II Springfield, Sangamon Mine, Sangamon Coal Co.
- III Eldorado, Mine No. 8, O'Gara Coal Co.
- IV Marion, Chicago & Big Muddy Coal Co.
- V Herrin, Squirrel Ridge Mine, Chicago & Carterville Coal Co.
- VI DuQuoin, Greenwood, Davis Coal Co.
- VII Belleville, Suburban Coal Mining Co.
- VIII O'Fallon, Mine No. 2, St. Louis & O'Fallon Coal Co.

	I	II	III	IV	V	VI	VII	VIII
Weight of Coal in grams	109	139	180	183	146	134	138	153
Total Volume of Gas Enclosed in cc. at Normal Temperature and Pressure	873	849	816	814	843	853	850	837
Per cent by Volume								
CO ₂	.48	.94	.68	1.87	.25	1.23	1.11	1.62
O	.16	.13	0.	0.	.25	0.	0.	1.45
CH ₄	0.	0.	6.28	0.	2.17	0.	0.	0.
N	99.36	98.93	93.04	98.13	97.33	98.77	98.99	96.93

These two sets of analyses give some indication of the nature of the alterations that are going on when coal is exposed, but give no information as to the composition of the gas remaining in the coal. In addition, the samples were of various sizes of coal that had been broken from the face of the seam and they had been subjected to more or less exposure, even though but for short periods. In order to get coal closely representative of the material as it occurs in the seams, a set of samples of drill dust was collected in the following manner. As the drillings fell from the hole, they were collected in an ordinary half-liter fractionating flask fitted with a stopcock at the side tube. When the flask was filled it was sealed by a rubber stopper which was coated with the rubber resin vacuum cement. These flasks were taken to the laboratory as soon as possible, all the gases contained therein were removed by means of a mercury air pump and were collected over mercury. This portion of the gas is designated in the tables as *last air*. The flasks were then allowed to stand for several days after which they were again connected with the air pump and any gas that had been evolved was removed.

In order to have some extreme types of laboratory weathered samples to compare with the fresh drillings, a set of coals that had been used for some previous tests was evacuated in the above manner. These were portions of mine samples about two years old and had been quartered, reduced to buckwheat size, air-dried and enclosed in air-tight containers. These samples were transferred to flasks, as shown by *J* in Fig. 1, and evacuated by the mercury pump. The results are given in pairs, the fresh drillings being placed by the side of the samples two years in storage. These two series correspond as to location of the mines, so comparison of the changes in the occluded gases can be made by inspection of Table IX.

The striking feature of the above table is the large amount of combustible gases liberated by the fresh drillings. While this amounts to as much as 30 cc. per 100 grams, in the fresh samples, no such gases were detected in the old lots. However, it must be understood that the relative amounts of gas in coal from these various mines can not be critically judged from these analyses, as some of the working faces have been within short distances of long standing exposures¹. Some idea of the rapidity of transpira-

¹A universal shutdown in the Illinois coal mines during April and a part of May, 1908, made it impossible to get samples representative of continuous workings.

tion of occluded gases from exposed faces can be gathered from the following data.

As a drill hole was driven, the dust from the first $2\frac{1}{2}$ feet was collected in one flask, while that from the last 3 feet was sealed in a separate container. As can be seen in Table X, the sample further from the exposed face contained more occluded gas and had less changes produced in what did remain.

TABLE IX

COMPARISON OF GASES FROM COALS OF DIFFERENT EXPOSURE PERIODS

- I Springfield, Sangamon Mine, Sangamon Coal Co., fresh drillings.
- II Springfield, Sangamon Mine, Sangamon Coal Co., face sample, 2 years old.
- III Herrin, Squirrel Ridge Mine, Chicago & Carterville Coal Co., fresh drillings.
- IV Herrin, Squirrel Ridge Mine, Chicago & Carterville Coal Co., face sample 2 years old.
- V Clifford, Mine No. 8, Big Muddy Coal & Iron Co., fresh drillings.
- VI Clifford, Mine No. 8, Big Muddy Coal & Iron Co., face sample 2 years old.
- VII Marion, Mine No. 3, Peabody Coal Co., fresh drillings.
- VIII Marion, Mine No. 3, Peabody Coal Co., face sample 2 years old.
- IX Westville, Mine No. 44, Dering Coal Co., fresh drillings.
- X Westville, Mine No. 44, Dering Coal Co., face sample 2 years old.

Part 1 Last Portion of Air

	I Fresh	II Old	III Fresh	IV Old	V Fresh	VI Old	VII Fresh	VIII Old	IX Fresh	X Old
Time of Standing, days	7	9	14	2	13	4	13	6	7	1
Weight of Coal, grams	261	209	220	205	244	204	217	204	231	108
Volume of Gas cc. (a)	141.2	96.6	192.1	33.5	287.4	40.6	160.6	63.3	197.2	38.4
Cc. of Gas per 100 g. (b)	54.21	46.2	87.4	16.37	117.8	19.78	74.2	30.97	85.50	35.66
CO ₂	2.12	1.91	3.37	1.27	6.65	1.23	3.27	.54	10.34	0.
O	2.87	2.06	.94	2.54	.58	2.75	.95	5.04	.95	7.90
CH ₄	12.22	0.	18.70	0.	28.22	0.	1.57	0.	19.81	0.
N	37.00	42.23	64.05	12.56	72.40	15.81	68.20	25.39	54.40	27.76
Per cent by Volume										
CO ₂	3.92	4.15	3.86	7.80	5.56	6.80	4.43	1.79	0.	12.09
O	5.30	4.46	1.04	15.50	.49	13.80	1.28	16.25	22.20	1.11
CH ₄	22.53	0.	21.79	0.	32.44	0.	2.12	0.	0.	23.17
N	68.65	91.39	73.31	76.70	61.51	79.4	92.17	81.96	77.80	63.63

Part 2 Gas Removed by Vacuum

	I Fresh	II Old	III Fresh	IV Old	V Fresh	VI Old	VII Fresh	VIII Old	IX Fresh	X Old
Time of Standing, days	13	8	12	10	13	12	13	11	13	10
Weight of Coal, grams	261	209	220	205	244	204	217	204	231	108
Volume of Gas cc. (a)	26.9	14.9	48.8	1.9	76.4	5.8	20.4	20.5	26.0	1.1
Cc. of Gas per 100 g. (b)	10.31	7.12	22.18	1.08	31.30	2.84	9.4	10.04	11.26	1.02
CO ₂	1.84	2.74	1.68	....	4.63	.69	3.18	2.01	3.51	.56
O	.50	.10	.14	....	.29	.15	0.	0.	.82	.10
CH ₄	6.14	0.	19.21	....	22.20	0.	.09	0.	2.17	0.
N	1.83	1.27	1.21	....	4.18	1.88	6.13	8.03	4.76	.36
Per cent by Volume										
CO ₂	17.85	80.50	7.58	....	14.79	24.20	33.84	20.0	32.09	54.60
O	4.83	1.30	.61	....	.92	5.90	0.	0.	7.32	9.90
CH ₄	59.59	0.	86.37	....	70.93	0.	1.00	0.	19.26	0.
N	17.73	18.20	5.44	....	13.36	69.90	65.16	80.0	41.33	35.50

(a) At 0° C and 760 mm. pressure. (b) Figured to coal as sampled.

TABLE X

GASES FROM COAL DRILLINGS TAKEN AT VARYING
DISTANCES FROM THE FACE OPENING

I	Westville, drillings from first 2½ feet of hole, last air.
II	" " " last 3 " " " " "
III	" " " first 2½ " " " gas by vacuum.
IV	" " " last 3 " " " " "

	I	II	III	IV
Time of Standing, days	7	7	13	13
Weight of Coal	182	231	182	231
Volume of Gas at 0° C. 760 mm.	174	197.2	9.6	26.0
Cc. of Gas per 100 g. of coal	95.60	85.50	5.27	11.26
CO ₂	7.23	10.34	1.76	3.51
O	.59	.95	0.	.82
CH ₄	11.29	19.81	2.30	2.17
N	76.40	54.40	1.21	4.76
Per cent by Volume				
CO ₂	7.57	12.09	33.33	32.09
O	.62	1.11	0.	7.32
CH ₄	11.73	23.17	43.74	19.26
N	80.08	63.63	22.93	41.33

In addition to the loss of combustible gases, the fresh samples of drillings showed more extensive absorption than did the laboratory weathered ones. From this it may be concluded either that the oxygen has entered into some combination with the coal itself, or that a reaction has taken place, resulting in the formation of carbon dioxide. The presence of considerable amounts of carbon dioxide in the gases from the fresh samples seems to bear out the latter conclusion, although it does not completely replace the oxygen of the air. It may also be possible that the carbon dioxide formed and taking the place of the occluded gases is only given off at higher temperatures. That this is true to some extent is shown by the fact that 69% of the gases removed from one of these fresh samples at 100°C. consisted of carbon dioxide. This phase of the matter is receiving further study.

It is certainly true that this absorption of oxygen takes place either contemporaneously or as soon as the gases escape from the fresh coal. A study of some of the stages of this absorption or oxidation can be made from Table XI.

TABLE XI

AVIDITY OF OLD AND FRESH COAL FOR OXYGEN

- I Atmosphere surrounding old face sample in contact with large volume of air for 2 years.
- II Old face sample sealed in fresh air 2 days, then evacuated.
- III Drillings, sealed 14 days.
- IV " in vacuum 12 days.
- V " second air in contact with coal 7 days.

	I	II	III	IV	V
Weight of Coal, grams	146	205.5	220	220	220
Volume of Gas, cc.	843	33.5	192.1	48.8	130.4
Per cent by Volume					
CO ₂	.25	7.80	3.86	7.58	1.63
O	.25	15.50	1.04	.61	.37
CH ₄	2.17	0.	21.79	86.37	14.14
N	97.33	76.70	73.31	5.44	83.86

In this table all samples were from the same mine. No. I and II were partially air-dried face samples, which had been sealed in Putnam jars for some two years. From No. I the surrounding air in the container was collected by displacement and analyzed.

No. II was left in one of the sealed fractionating flasks for two days. At the end of that time both the surrounding air and some of the enclosed gases were removed by means of the air pump. No. III is a flask of fresh drillings from which the surrounding air and occluded gases were removed by vacuum, as above. No. IV is the analysis of the further gas given off after the surrounding air had been removed and the flask had stood in a vacuum for twelve days. No. V is the analysis of the air that had been readmitted to the evacuated flask and left in contact with the coal for seven days.

Further comparison of the rapidity of oxidation can be made from Table XII. All samples were from the same mine. No. I and II had been in laboratory containers for over two years. Two portions were transferred to the flasks and left in contact with normal air for two and six days respectively.

TABLE XII

RAPIDITY OF OXIDATION IN FRESH AND OLD SAMPLES OF COAL

- I Old face sample sealed 2 days, last air.
 II " " " second air in contact 6 days.
 III Fresh drillings, sealed 14 days, last air.
 IV Drillings, second air in contact 7 days.
 V Fresh drillings, sealed 13 days, last air.
 VI Drillings, second air in contact 8 days.

	I	II	III	IV	V	VI
Weight of Coal, grams	204	204	220	220	244	244
Volume of Gas at 0°C & 760 mm.	40.6	253.1	192.	130.4	287	157.
Cc. per 100 g. of Coal	19.78	124.2	87.40	59.28	117.7	64.4
CO ₂	1.23	1.95	3.37	.97	6.65	2.02
O	2.75	7.24	.94	.22	.58	.15
CH ₄	0.	0.	19.04	8.38	13.14	8.84
N	15.81	115.0	64.05	49.71	97.0	53.39
Per cent by Volume						
CO ₂	6.80	1.57	3.86	1.63	5.56	3.14
O	13.80	5.83	1.04	.37	.49	.23
CH ₄	0.	0.	21.79	14.14	11.14	13.70
N	79.40	92.60	73.39	83.86	82.81	82.93

The preceding results have thrown some light upon the changes produced by the deterioration of sealed laboratory samples but contain no data on samples subjected to outside exposure. Table XIII gives a comparison between samples of fresh

TABLE XIII

COMPARISON OF ACTIVITY AS BETWEEN SEALED AND
EXPOSED SAMPLES OF COAL

I	Westville, Mine No. 44, Dering Coal Co., fresh drillings, sealed.
II	" " " " " " " " exposed screenings, 15 mo. old.
III	" " " " " " " " " " 2 " "
IV	Marion, Mine No. 3, Peabody Coal Co., fresh drillings.
V	" Binkley, Miles Coal Co., outcrop coal.
VI	Springfield, Sangamon Mine, Sangamon Coal Co., fresh drillings.
VII	" " " " " " " " screenings, 2 mo. old.

Part 1 Last Portion of Air

	I Fresh	II Ex- posed	III Ex- posed	IV Fresh	V Ex- posed	VI Fresh	VII Ex- posed
Time of Standing, days	7	3	6	13	19	7	3
Weight of Coal, grams	231	200	200	217	224	261	200
Volume of Gas, 0°C. 760 mm.	197.2	44.2	55.8	160.6	134.3	141.2	240.5
Cc of Gas per 100 g.	85.50	22.10	27.9	74.2	60.0	54.21	120.3
CO ₂	10.34	1.40	.25	3.27	3.38	2.12	3.03
O	.95	3.25	5.75	.95	.38	2.87	22.09
CH ₄	19.81	0.	0.	1.57	.54	12.22	.66
N	54.40	17.45	21.90	68.20	55.70	37.00	94.47
Per cent by Volume							
CO ₂	12.09	6.34	.90	4.43	5.64	3.92	2.51
O	1.11	14.71	20.61	1.28	.64	5.30	18.36
CH ₄	23.17	0.	0.	2.12	.54	22.53	.55
N	63.63	78.95	78.49	92.17	93.18	68.65	78.58

Part 2. Gas Removed by Vacuum

	I Fresh	II Ex- posed	III Ex- posed	IV Fresh	V Ex- posed	VI Fresh	VII Ex- posed
Time of Standing, days	13	14	13	13	7	13	13
Weight of Coal, grams	231	200	200	217	217	261	200
Volume of Gas, 0°C. 760 mm.	26.0	26.9	16.8	20.4	19.9	26.9	23.9
Cc of Gas per 100 g.	11.26	13.45	8.4	9.40	8.88	10.31	11.95
CO ₂	3.51	1.4	2.85	3.18	2.99	1.84	2.39
O	.82	2.8	.7	0.	.36	.50	.81
CH ₄	2.17	.15	.6	.09	.10	6.14	2.39
N	4.76	9.10	4.25	6.13	5.43	1.83	6.36
Per cent by Volume							
CO ₂	32.09	10.41	33.93	33.84	33.67	17.85	20.00
O	7.32	20.82	8.33	0.	4.02	4.83	6.78
CH ₄	19.26	1.12	7.15	1.00	1.05	59.59	20.00
N	41.33	67.65	50.59	65.16	61.26	17.73	53.22

drillings and samples exposed to the weather. No. I is a sample of fresh drillings from Westville, while No. II was collected from the surface of a pile of $1\frac{1}{2}$ inch screenings from the same mine and had been stored outside for fifteen months. No. III is from the surface of a pile of the same screenings that had been stored outside for two months. No. IV is a sample of fresh drillings from Marion, while No. V is from an outcrop of the same seam one mile from the place where No. IV was taken. This outcrop had been exposed for one year. No. VI is a sample of drillings from Springfield, while No. VII was collected from the surface of a pile of $1\frac{1}{2}$ inch screenings from the same mine. These screenings had been stored outside for two months. Samples of each type were sealed in the evacuating flasks, *J*, of Fig. 1, together with normal air for periods of from three to nineteen days, indicated in the following table. Upon applying the vacuum, the first portion of air, to about 150 mm. pressure, was discarded. The last portion secured by carrying the vacuum to the limit gives essentially the composition of the gases contained in the coal proper, as shown in Table XIII, Part 1. Without the readmission of air the flasks were set aside for varying periods and a second application of the vacuum gave results as shown in Part 2.

VI SUMMARY

It seems evident from a study of the results presented in the foregoing pages, that two active processes are set up immediately upon the liberation of coal from the vein. The first is an exudation of hydrocarbons, mainly consisting of marsh gas (CH_4); the second is an absorption of oxygen. There can be little question, moreover, that these alterations proceed simultaneously. In Tables IX and X, for example, on pages 21 and 22, there are present in the gases from all the samples of fresh drillings, notable quantities of methane, ranging from 18% to 86% of the various gas volumes. At the same time the oxygen present has dropped down in a very positive manner, in some cases even reaching the vanishing point. That this transpiration of gases is interdependent and is of the nature of an osmotic exchange can hardly be affirmed as an explanation of the phenomenon. On the contrary, there seems to be evidence that the gases operate independently of each other. Take for example the figures

for marsh gas. In the case of the samples listed in Table IX, the exudation of CH_4 seems to have spent itself in those samples held in laboratory containers for two years. In no case is there evidence of further liberation of this gas, even with thorough application of the vacuum. Table XI shows a similar condition, in that an evacuation of the gases from the two year old sample, as in No. II, shows no marsh gas present. Similar results are seen in samples No. I and II in Table XII. In Table XIII the completion of this exudation would seem to be reached after two months, though it is well to note that by forcing, as with a vacuum in the second part of this table, the two months old samples may be made to yield more methane, though in relatively small quantities.

On the other hand, the avidity of the coal for oxygen seems to be pronounced at the very beginning of the exposure of the freshly mined material, and while there are a number of cases where a certain agreement seems to exist between the in-going and the out going marsh gas, still there are more cases where the absorption of oxygen is pronounced without any evidence of marsh gas being present. For example, attention may be called especially to samples No. II, IV, VI, and VIII, in Table IX. In all of these cases the oxygen-nitrogen ratio shows a positive diminution of the oxygen from the normal ratio of approximately 1:4 with practically no evidence of marsh gas being present. While the statement, therefore, may be modified by further study, it seems fair to conclude, for the present, that there is no necessary connection, at least of a strictly chemical nature, between the exudation of marsh gas and the absorption of oxygen.

Again, the liberation of CH_4 , while very active in the first few days after removal of the coal from the ground, diminishes in amount quite rapidly till, after the second month, there is very little of this gas in evidence. The activity of the coal for oxygen, on the contrary, seems to be of longer duration. In Table XII, samples No. I and II were collected June 1, 1906. The tests for the table were made in May and June, 1908. There is marked absorption of oxygen in sample No. I after two days' exposure in the flask to normal air, while No. II, with five days' exposure, shows still further reduction in the oxygen ratio without accompanying evidence, also, it should be noted, of marsh gas. Similarly, sam-

ples No. II, IV, VI, and VIII, of Table IX, show a marked avidity for oxygen after two years from time of collecting.

These facts have a direct bearing on the topic of deterioration, as substantially defining the limit as to time of that form of alteration. While varying somewhat in different coals, the loss of hydrocarbons for the most part is practically complete at the end of two months. These facts have a bearing also upon the matter of weathering, and indirectly upon the matter of spontaneous combustion. The absorption of oxygen is undoubtedly closely associated with both of these phenomena. Our studies upon the weathering processes coincide with these studies in gases, namely, that in all probability this low type of oxidation extends over an indefinite length of time. Moreover, while under normal conditions there is effected but a very slight oxidation and loss of fuel values, the conditions are favorable, as, for example, upon an increase of temperature, for bringing about a very rapid combination with oxygen even to the point of combustion.

How far this absorption of oxygen is a chemical reaction, or low combustion resulting in CO_2 and H_2O , and how far it is an absorption into the molecular structure and composition of the coal must be left for further study.

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TESTS OF TUNGSTEN LAMPS

BY

T. H. AMRINE

AND

A. GUELL



UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 33

MARCH 1909

TESTS OF TUNGSTEN LAMPS

BY T. H. AMRINE, ASSOCIATE IN ELECTRICAL ENGINEERING
DEPARTMENT, ENGINEERING EXPERIMENT STATION

AND

A. GUELL, RESEARCH FELLOW, ELECTRICAL ENGINEERING

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I. INTRODUCTION

When the tungsten incandescent lamp was put on the market, about a year and a half ago, its high efficiency and excellent quality of light were in a large measure offset by the extreme fragility of its filament, its uncertain life and its high price. For instance, in October, 1907, when German tungsten lamps were just being introduced into this country, the Engineering Experiment Station bought a dozen of the 40-watt size (the smallest obtainable at that time) for testing purposes, at a cost of \$1.50 each. They came by express, packed with as much care and skill as was thought necessary, but when the lamps were received only five of the twelve had unbroken filaments, and these five had an average life of 50 or 75 hours only. This experience was a typical one with tungsten lamps at that time.

Since then many companies have entered the field of tungsten lamp manufacture, and they have all striven to overcome the faults common to those early lamps. In their attempts to make a lamp that would better withstand shipment and handling, that would not blacken and burn out early in its life and that could be burned in other than the vertical pendant position necessary with the first lamps, the manufacturers have developed several types of tungsten lamps. These differ considerably in two respects: (1) the method of manufacture; and (2) the scheme of mounting the filaments.

This bulletin describes a study of three prominent types of tungsten lamps, differing considerably in the above respects. This study was made with the idea of bringing out, as far as possible, the good as well as the poor points in the construction and manufacture of each type. There are included the results of tests showing what may be expected of the present day low wattage tungsten lamps in the way of life, maintenance of candle power and efficiency under different operating conditions.

II. DESCRIPTION OF LAMPS

Of the lamps chosen for the tests, one type was of American and two were of German manufacture. They will be designated as the *P*, *D* and *C* lamps, respectively. They represented three of the principal processes used in the manufacture, and three common schemes of mounting tungsten lamp filaments at the time the tests were started. All lamps tested were chosen from a lot of 100 of each type of lamp.

Rating.—All three lamps were rated at 25 watts at 110 volts and advertised to give an efficiency of 1.25 watts per candle-power. Fig. 1, 2 and 3 show the candle-power and watt per candle values for the individual lamps when new, and the average curve drawn through these points for the 100 lamps of each kind. It will be seen from the curves that the average watt per candle efficiency of the *C* lamps is somewhat poorer than the others. This can perhaps be explained by the fact that its filament is supported by three times as many spires as the other two, and hence more of

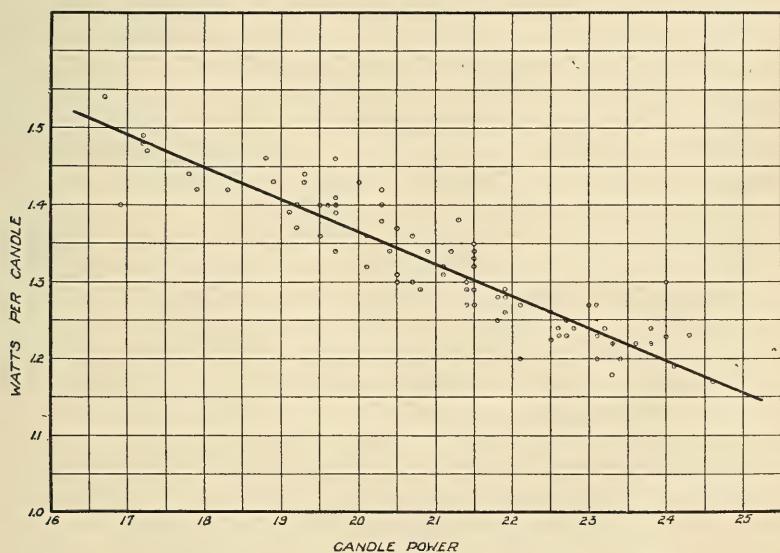


Fig. 1

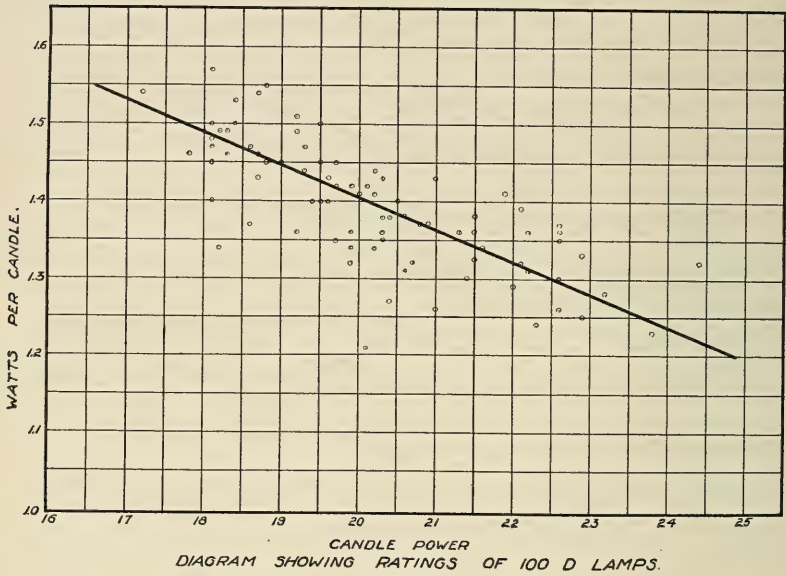


FIG. 2

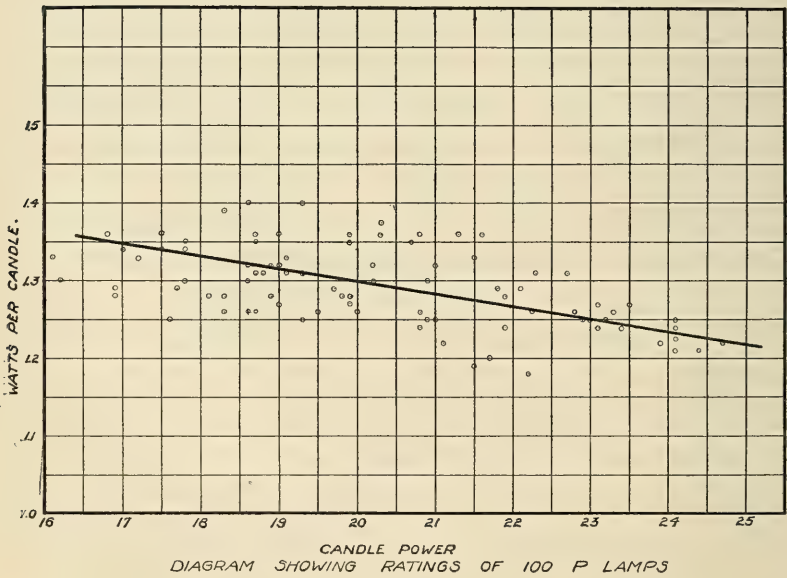


FIG. 3

the filament is kept cooled below incandescence. In the *D* and *P* lamps, each one of the tip end spires cools approximately $1/8$ inch of filament, so that it produces little or no light, while the spires at the base end each cool approximately $1/16$ inch. This makes about one inch of filament in each lamp that acts merely as a resistance. In the *C* lamp there are 16 spires, each cooling a short length, so that there are about 2 1-2 inches of ineffective filament so far as light production is concerned. This would account for the difference in efficiency between this lamp and the other two, since the main part of the filaments is operated at approximately the same temperature.

Filaments.—The filaments of the American lamp (*P*) were manufactured by the paste or Auer process. In this method, which is similar to the one used in making ordinary carbon filaments, finely powdered tungsten is mixed with a suitable binder, such as sugar or some other organic substance, and the resulting paste is squirted through a diamond die under great pressure. The moist filament so formed is then heated in an atmosphere of steam and hydrogen to remove the carbon of the binding material. This leaves a filament of almost pure tungsten. The filament, as mounted in the lamp, consists of four hairpin loops connected in series and mounted upon supporting spires. Connections between the loops are made at the base end of the stem by fusing together the filaments and the spires. The filaments are hung loosely on the spires so as to allow for the contraction that takes place after they have been burned for a time.

The filament of the first German lamp (*D*) is made by the deposition process. In this method a fine filament of carbon is heated in an atmosphere of some compound of tungsten, for instance, oxychloride of tungsten. This causes the metal to be deposited in a shell upon the carbon core. By the application of heat the tungsten and carbon are made to unite chemically to form tungsten carbide, which is then reduced and the carbon removed by a method similar to that employed in the paste process. The

filament in this lamp also consists of four loops, but the supporting spires at the tip end of the stem are very thin and flexible springs, and the filament is kept under a slight tension by their action. The flexibility of these spires also permits contraction of the filaments to take place. The entire glass stem which carries the filaments is mounted between two coil springs, as shown in Fig. 4. The object of these springs is to absorb the jar and vibration to which the lamp may be subjected and so prevent breaking the filament. Connections between the filament and spires at the base end of the stem are made by means of pasted joints.

The second German lamp (*C*) is made by the colloid process. In this method colloidal tungsten is formed either by maintaining an arc between tungsten electrodes under some liquid, it may be water, or by reducing tungstic trioxide with potassium cyanide. This plastic colloidal mass is brought to the proper consistency, and is then squirted through a die to form a filament, as in the paste process. The filament so obtained is dried and is gradually brought to a white heat in a nonoxidizing atmosphere, and is thereby converted into the crystalline state. The filament in this lamp, too, consists of four loops, each of which is mounted in a peculiar spiral shape and hung loosely enough to permit of contraction. The joints between the filaments and the base spires are fused as in the *P* lamp.

TABLE 1
DIMENSIONS OF FILAMENTS

Lamp	Total Length inches	Diameter inches	Total Area of Surface square inches
<i>C</i>	19.87	.00138	.0859
<i>D</i>	15.92	.00202	.1009
<i>P</i>	19.27	.00163	.0987

The shapes of the bulbs and their comparative sizes are shown in Fig 4. The bulb of the *P* lamp is identical with that on the ordinary 16 candle-power carbon lamps in use in this country.

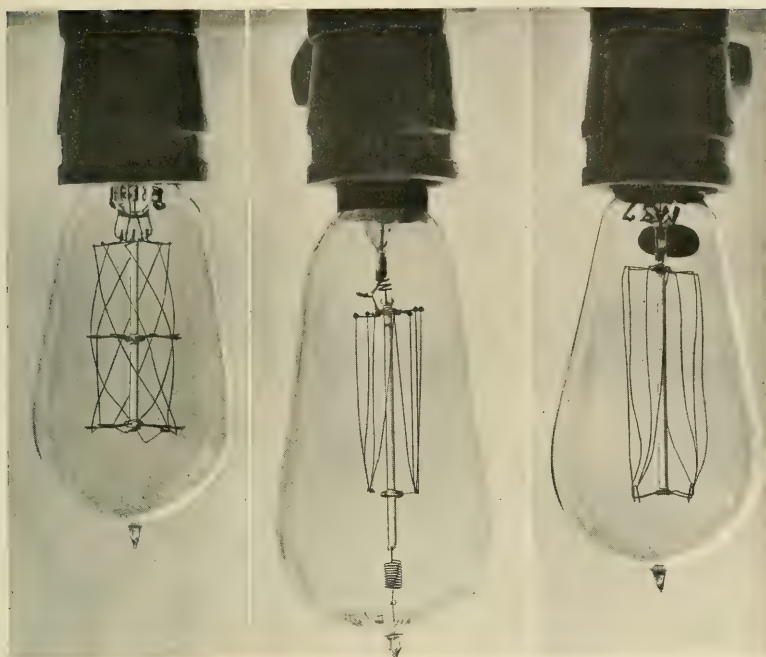
*C**D**P*

FIG. 4

III. ELECTRICAL CHARACTERISTICS¹

All three filaments, being of metal, have of course a positive temperature coefficient. Fig. 5 shows the temperature resistance curves for one lamp, selected at random from each of the three lots of lamps received. Fig. 6 is a curve between current and resistance that is typical of all three lamps.

As is the case with all lamps having filaments with a large positive temperature coefficient, the current, when first turned on, has a value several times greater than the normal operating value. Fig. 7 is a curve taken by means of an oscillograph, showing this change of current from the instant of starting. The very low re-

¹ In some of the curve sheets that follow, curves for only one kind of lamp are given. In these cases the results for all lamps are practically the same.

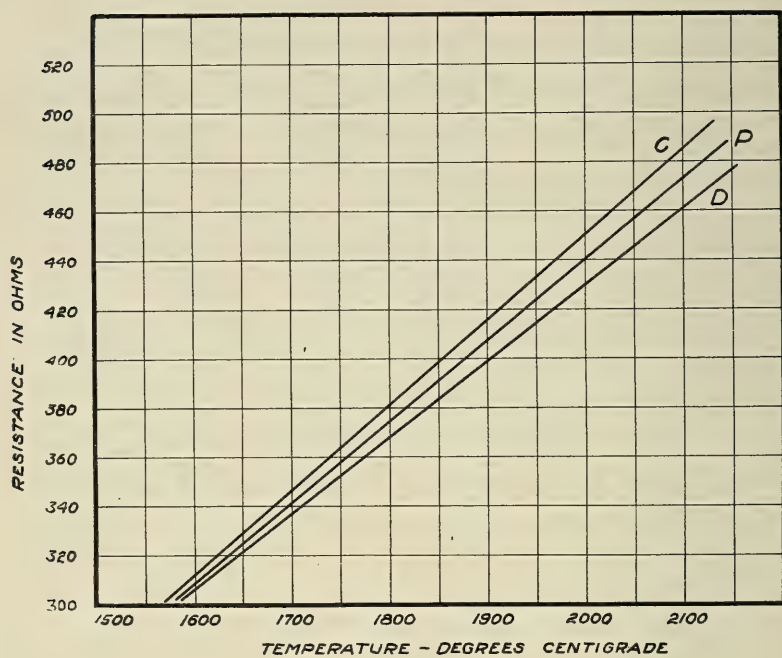


FIG. 5

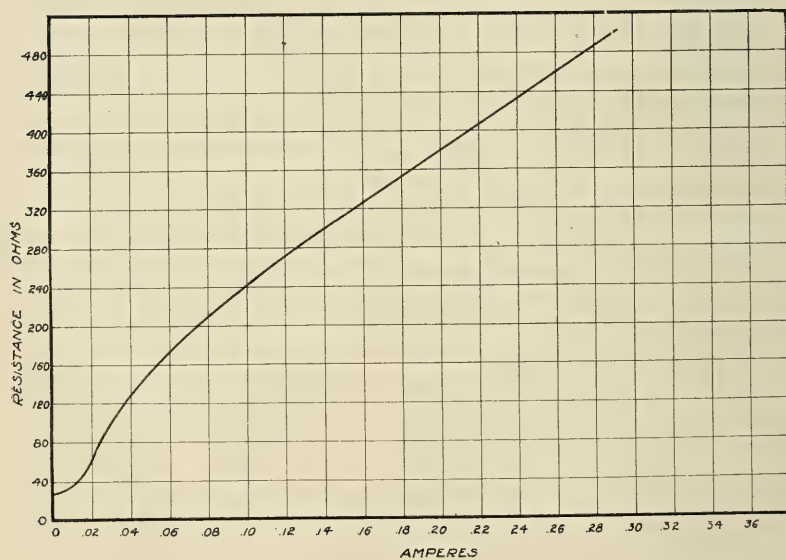


FIG. 6

sistance when the filament is cold, i. e., at zero current, as shown in Fig. 6, gives rise to a heavy rush of current at the first instant which quickly decreases, owing to the rapid increase of resistance as the filament heats up. This current rush, when the lamp is

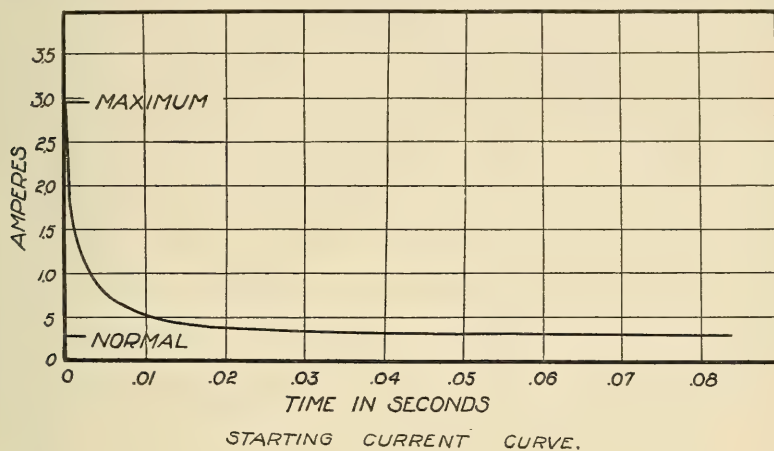


FIG. 7

turned on, causes the familiar flash or sudden rise in candle-power above normal, commonly known as overshooting.

The curves between candle-power and voltage, and between watts per candle and voltage, are shown in Fig. 8. The equation for the former, obtained by the method of least squares is

$$CP = 213.7 \times 10^{-8} \times E^{3.44}$$

Fig. 9 shows curves plotted between watts per candle and temperature,¹ for one lamp of each kind. These curves lie very close together, indicating that throughout the temperature range all three filaments give approximately equal watt per candle efficiencies for the same filament temperatures. Fig. 10 gives curves between temperature and spherical candle power per square inch of total filament area or emissivity. These indicate that the *C* lamp has the highest and the *D* lamp the lowest emissivity at all temperatures. This can be explained by an examination of the fila-

¹ The temperatures given in this bulletin are black body temperatures and are given as relative rather than absolute values.

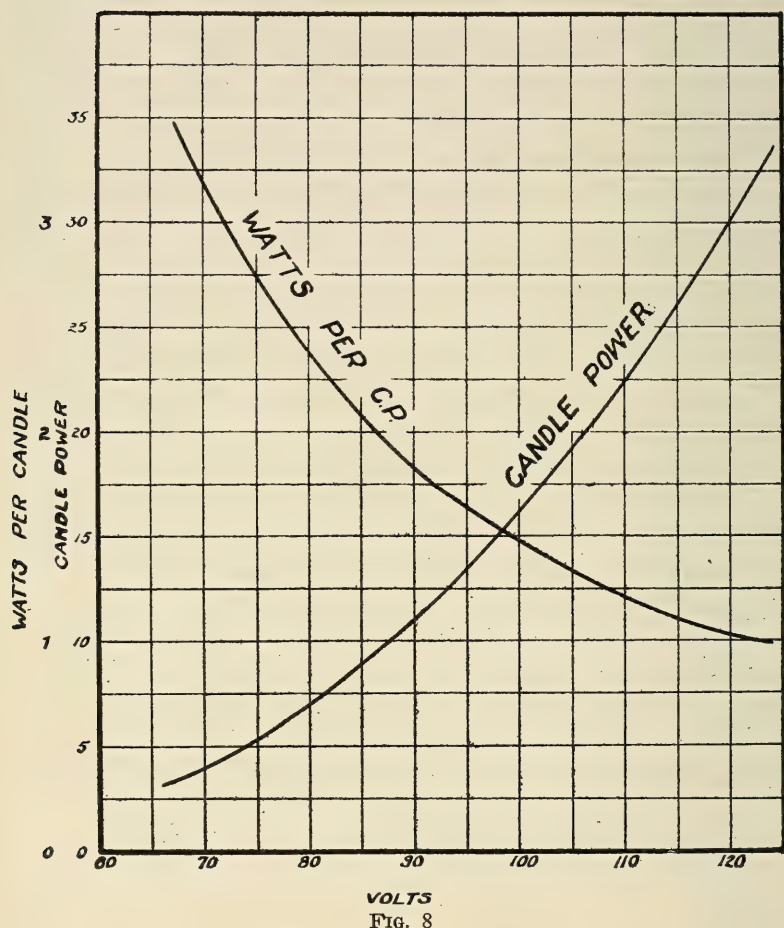


FIG. 8

ments under a microscope. Fig. 11 is a sketch of all three filaments showing their appearance when magnified. The *C* filament is seen to be the smoothest one of the three. It has no pits or protuberances, but has a smooth shiny surface broken only by what look like fine cracks similar to the fine check cracks sometimes seen in the glazes of porcelains. Such a smooth polished surface would naturally have a high emissivity. The *P* filament seems smooth, i. e., is free from knobs and protuberances, though it is covered with small depressions and wrinkles, probably due to the

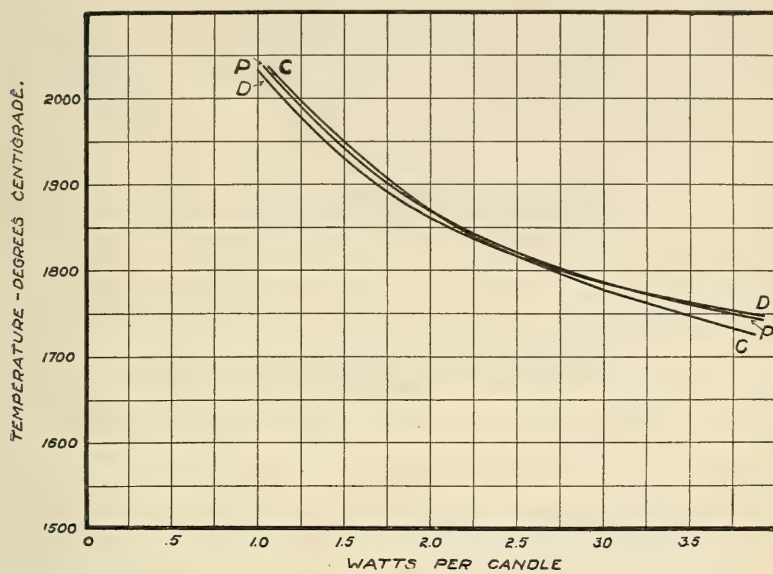


FIG. 9

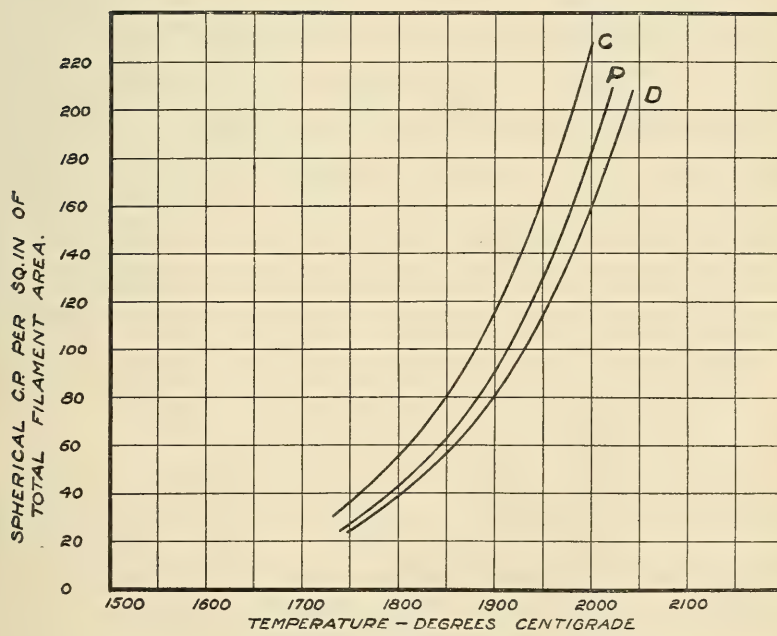
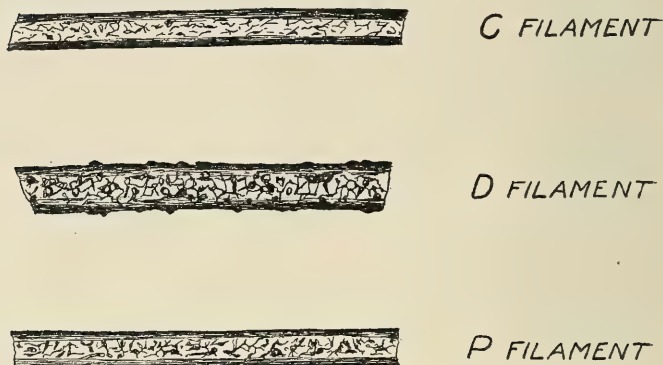


FIG. 10



SKETCH OF NEW FILAMENTS WHEN MAGNIFIED.

FIG. 11

removal of the carbon of the binder and the consequent shrinkage. The lines shown on the filament in the sketch represent fine wrinkles rather than cracks on the surface of the filament. These depressions and wrinkles on the surface make its emissivity somewhat less than that of the smoother *C* filament. The *D* filament is the roughest and most uneven of the three. It is covered with many knobs and protuberances, pits and large wrinkles. This rough surface naturally has a lower emissivity than the other two lamps.

IV. DISTRIBUTION

The horizontal distribution curves for all three lamps are approximately circles, as would be expected from the number and arrangement of the filaments. The vertical distribution curves are shown in Fig. 12, 13 and 14. The *D* lamp has the lowest tip candle power, the *P* lamp next, and the *C* lamp the highest,—nearly 10

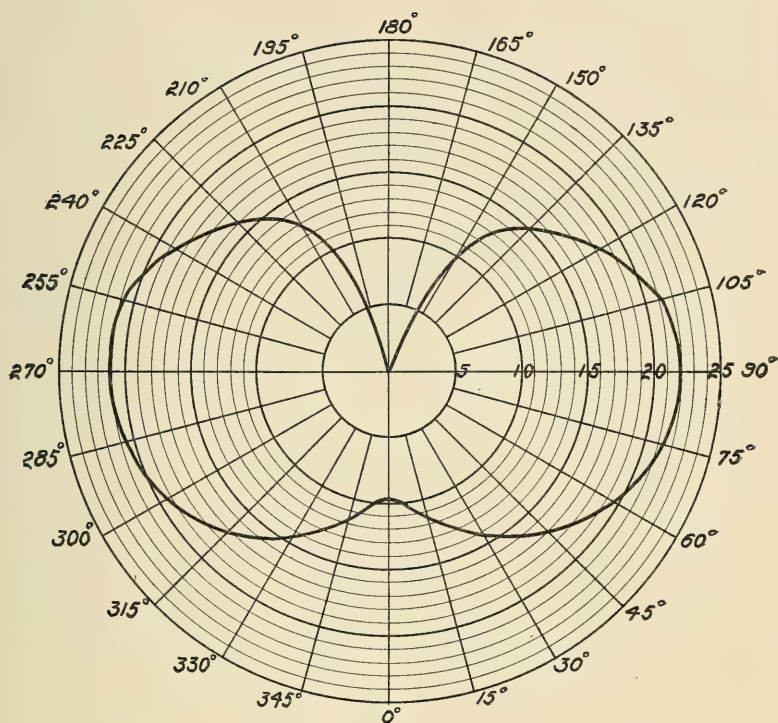
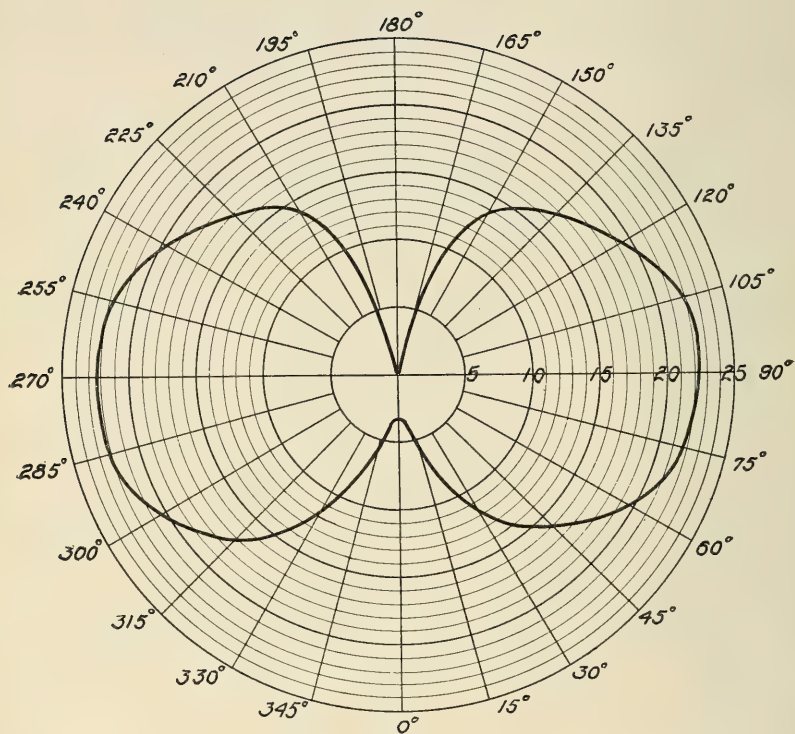
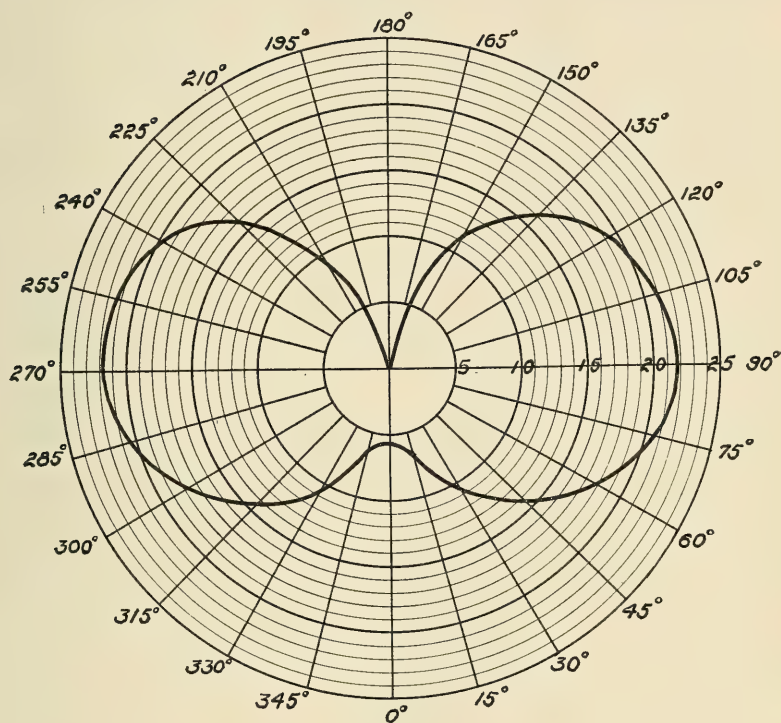
VERTICAL DISTRIBUTION OF C LAMP

FIG. 12



VERTICAL DISTRIBUTION OF D LAMP

FIG. 13



VERTICAL DISTRIBUTION OF P LAMP

FIG. 14

candle-power. The spherical reduction factors for the lamps are shown in the following table.

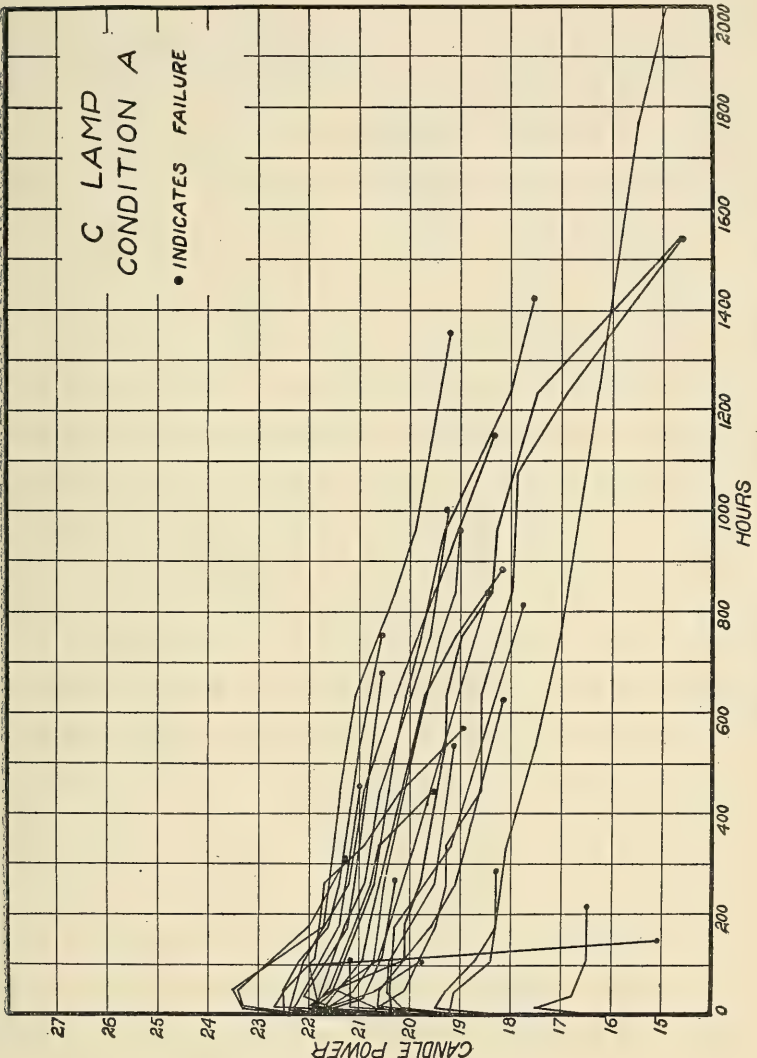
TABLE 2

Lamp	Mean Horizontal Candle Power	Mean Spherical Candle Power	Spherical Reduc- tion Factor
<i>C</i>	21.1	17.7	.840
<i>D</i>	22.2	16.2	.730
<i>P</i>	21.9	17.2	.785

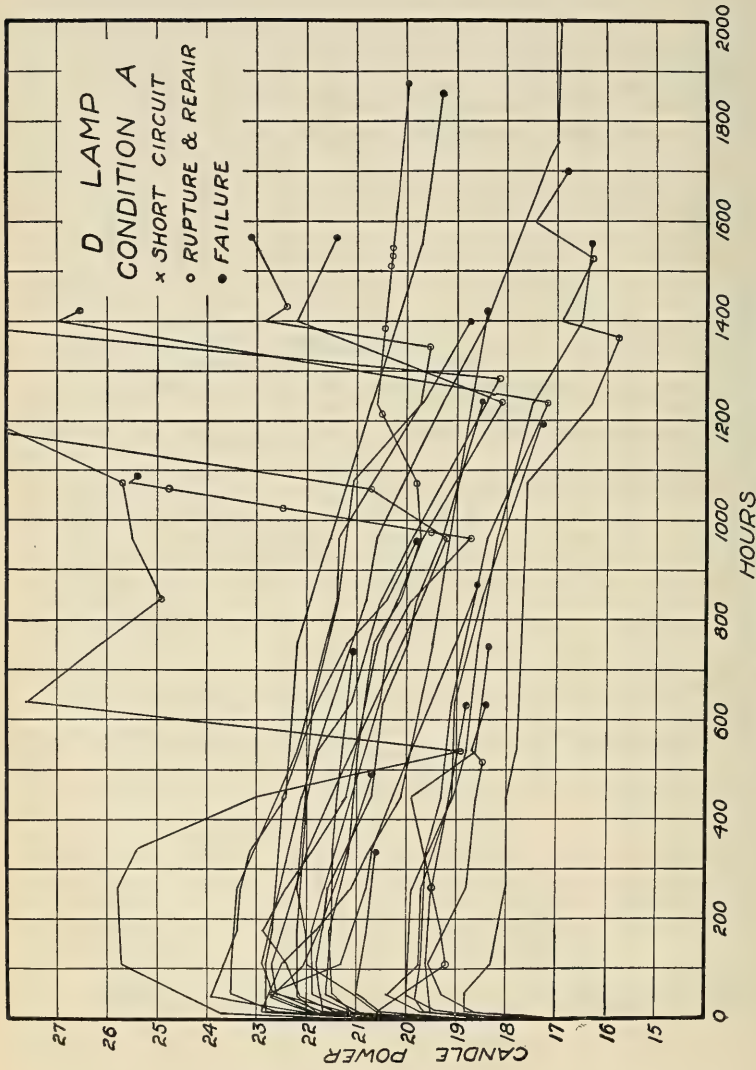
V. LIFE TESTS

For the life tests, 50 lamps of each kind were selected. Of these, 25 of each kind were burned upon a well-regulated voltage, supplied by a storage battery floating across constant voltage mains. The racks holding the lamps were supported by three coil springs in order to protect them from the vibration of the building. This condition will be designated as A, and represents exceedingly good operating conditions. The remaining 25 lamps of each kind were operated upon 60-cycle alternating current mains having a badly fluctuating voltage. The rack supporting these lamps was rigidly fastened to the floor and received all of the vibration of the building. This vibration was caused by the engines of the University power plant and the machines in the electrical laboratory two floors below. It was great enough to be easily felt by placing the hand on the rack, and the lamps themselves could be seen to vibrate. It was not so severe a vibration as that to which lamps would be subjected in many manufacturing plants, but it was severe enough to represent rather trying operating conditions. This condition will be designated as condition B. Fig. 15 to 20 show the candle-power performance of each lamp on the life tests for both operating conditions.

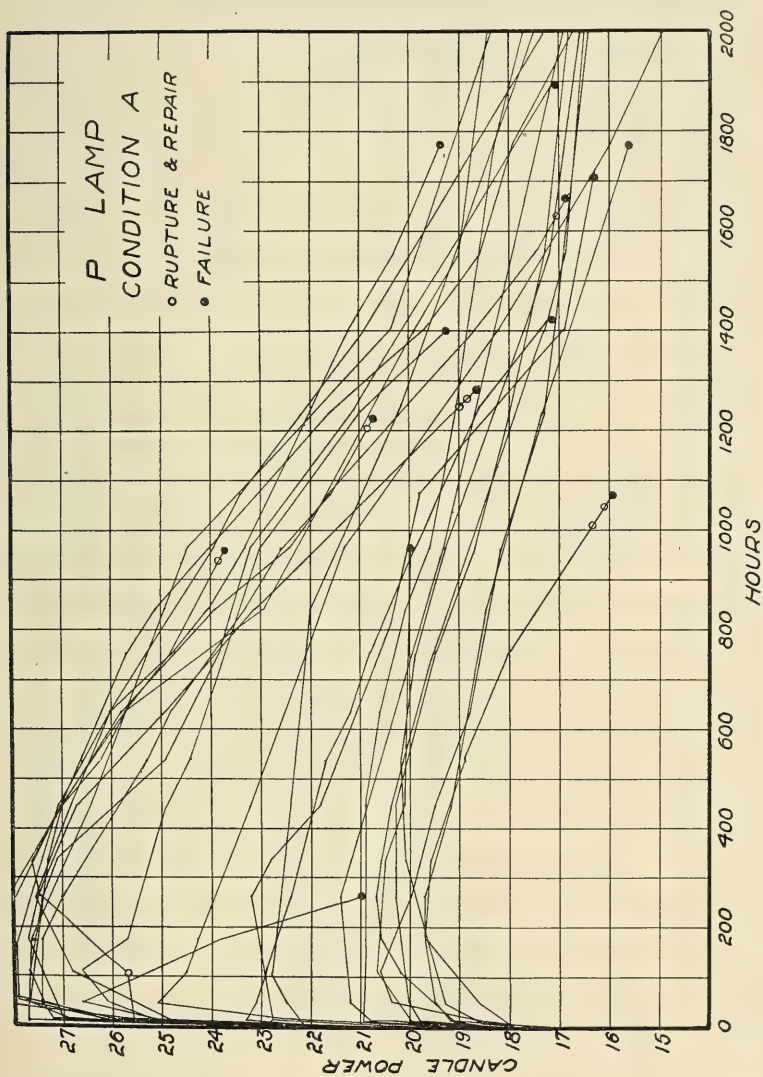
In the life test under condition A, readings were taken up to 2000 hours. At the end of this time there was one *C* lamp, one *D* lamp and thirteen *P* lamps still burning. The method of mounting the filament of the *C* lamp is such that it is seldom that a brok-

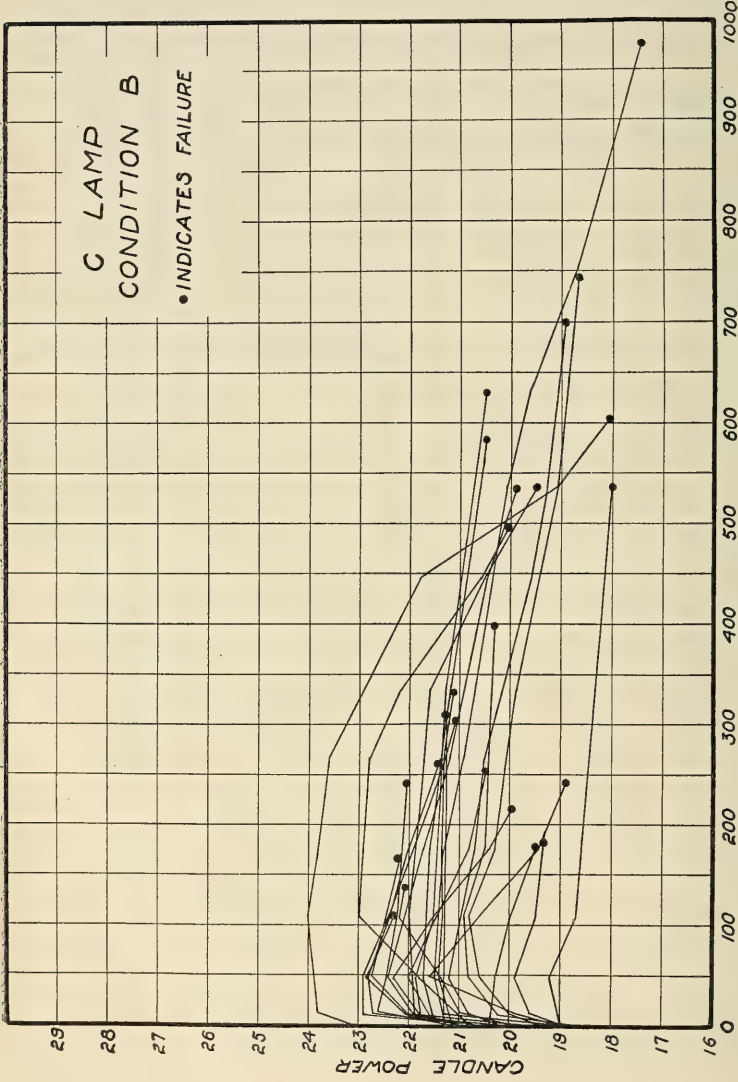


CURVES FOR C LAMPS - CONDITION A
FIG. 15

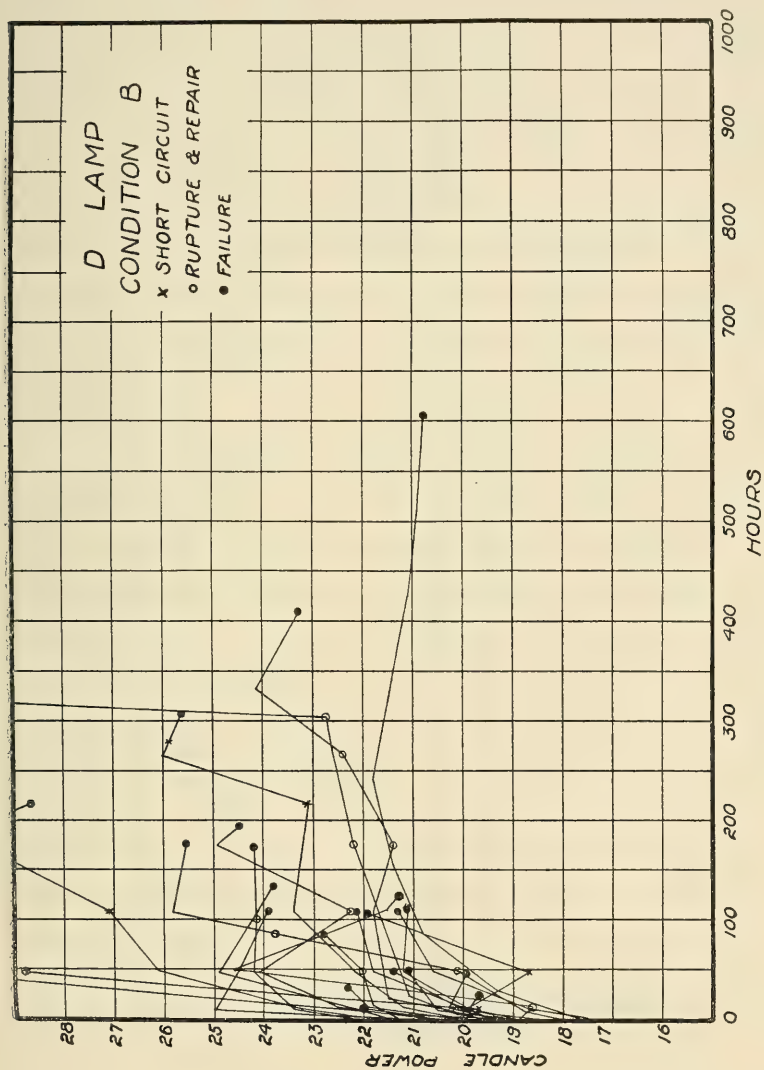


CURVES FOR D LAMPS - CONDITION A.
Fig. 16



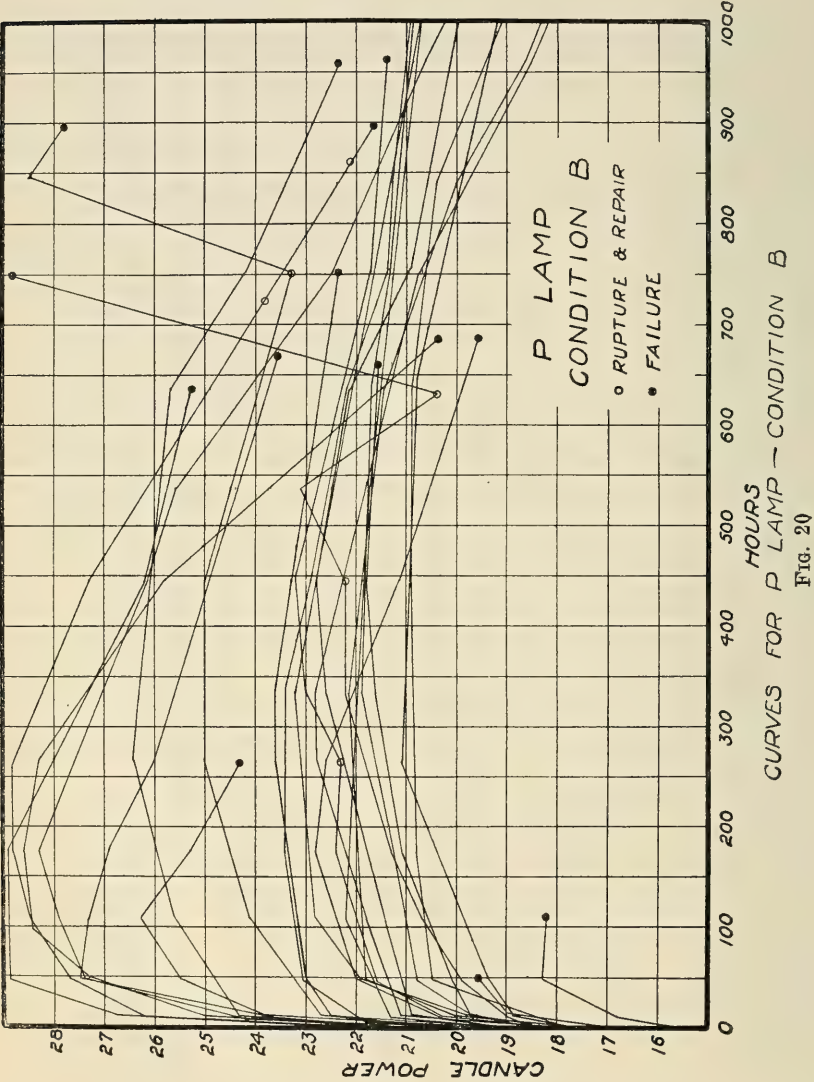


CURVES FOR C LAMP - CONDITION B.
FIG. 18



CURVES FOR D LAMP - CONDITION B.

FIG. 19



en filament can be repaired. For this reason, the curves for this lamp are very uniform, not showing the sudden increases and decreases that occur in the other lamps. In the *D* lamp the filaments can easily be welded when broken, in fact it is seldom that they can not be repaired after the first rupture. The sudden increases of candle-power that are so often noticeable in the curves for this type of lamp are caused by the welding and consequent decreases in the length of the filament.

In the *C* lamp, failures commenced after about 100 hours of burning and continued steadily for about 1500 hours, when all the lamps but one were gone. Failures in the *D* lamp began at about 300 hours, and at 1900 hours only one was burning. With the *P* lamp, there was one failure at about 300 hours, and then no more until after 900 hours, when they commenced to fail at the rate of about one every hundred hours.

Compared with the results under condition A, those under condition B are rather surprising. The *D* lamp, which made a satisfactory showing under good conditions of operation, did very poorly indeed when operated under adverse conditions. At the end of 600 hours all the lamps were burned out, having an average life of only 153 hours. The *C* and the *P* lamps, as might be expected, gave poorer results than when burning under condition A, but gave a much better average life than the *D* lamps, averaging 434 and 898 hours respectively.

The explanation of the poor life of the *D* lamp under condition B is very simple. These filaments are strung so that they are under tension and the stem upon which they are mounted is supported between two spiral springs. The object of these springs is to absorb the vibrations to which the lamp may be subjected, but the springs are so strong and the stem itself is so light that instead of protecting the filament from the vibrations, they simply take them up and hold them persistently, and of course set the tightly strung filaments to vibrating also. Often some of the filaments of the lamps on test would be seen to vibrate like a violin string with an amplitude that would occasionally become great enough to allow the two sections of a filament to touch and short

circuit themselves. A slight jar would often be sufficient to start these vibrations. It happens also that the tension, mass and length of some filament sections are such that when burned upon alternating current, persistent vibrations will be set up, due either to the presence of a stray¹ magnetic field or to the magnetic repulsion and attraction action of adjacent filament sections. Upon 50-cycle current, which is common in Germany where these lamps are manufactured, some filament sections would vibrate strongly when in a magnetic field, though there were fewer that would do so than there were on 60 cycles.

On account of being mounted without tension, the filaments of neither the *P* nor the *C* lamps would vibrate upon either the 60 or 50 frequency current, unless placed in a strong magnetic field, for instance, between the poles of a horse shoe magnet. When in a strong field, the filaments of both lamps formed a node in the middle and vibrated in two sections. After a long period of burning, the *P* lamp filaments would sometimes be sufficiently contracted to put some of the filament sections under tension, and then the same persistent vibrations would be noticed in them as in the *D* lamp.

VI. CANDLE-POWER MAINTENANCE AND CHANGE IN EFFICIENCY

The curves in Fig. 21 to 24 show the changes in candle-power and efficiency for the three lamps, the curves representing the mean performance of all the lamps tested. All three lamps show the increase in candle-power during the first few hours of burning, and the subsequent falling off in candle-power that is usual with incandescent lamps. The *P* lamp, however, shows the greatest change. It also maintains the highest average candle-power throughout the test, the *D* lamp being next and the *C* lamp the lowest. After 2000 hours' burning, the average candle-power of

¹ The only magnetic field that was near enough so that there was any possibility of its affecting the lamps was due to a direct current circuit carrying 7 amperes and it was at a distance of about 8 feet from the test rack so that its effect must have been very small.

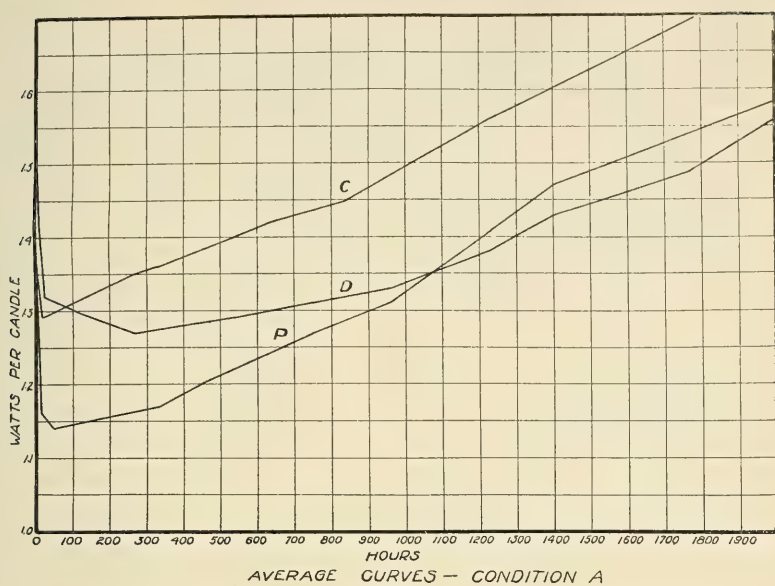


FIG. 21

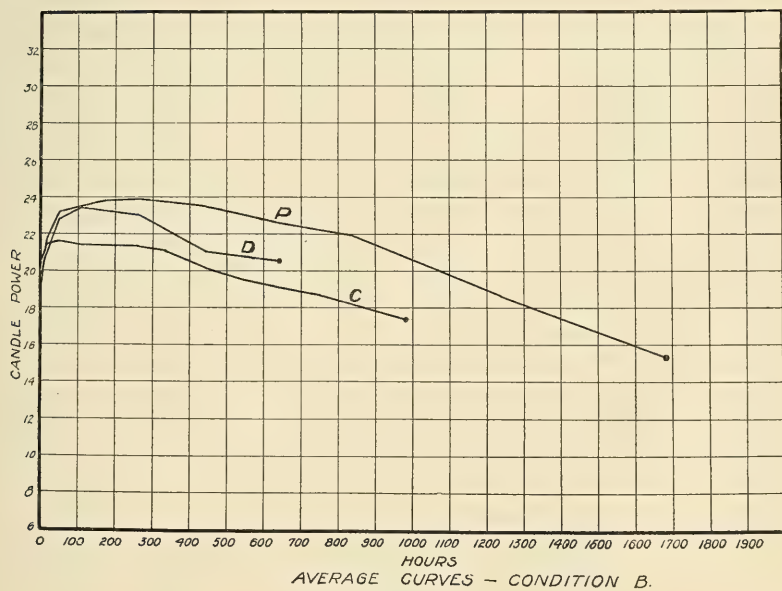


FIG. 22

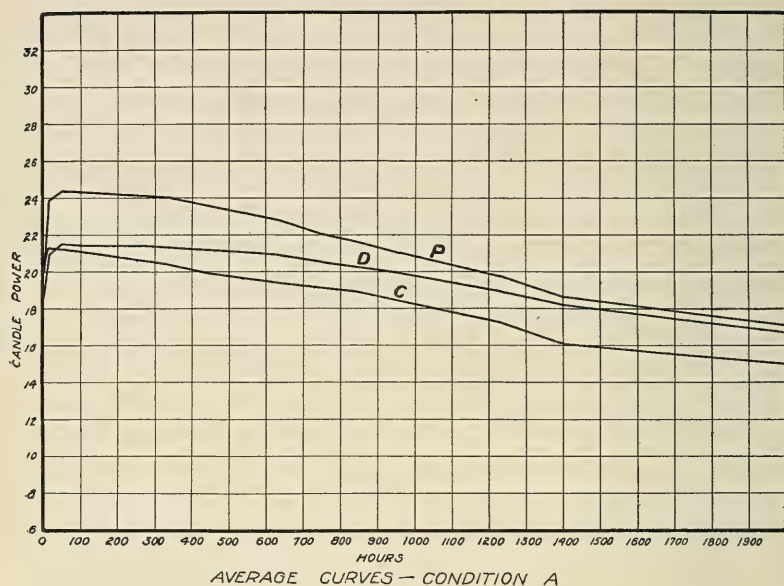


FIG. 23

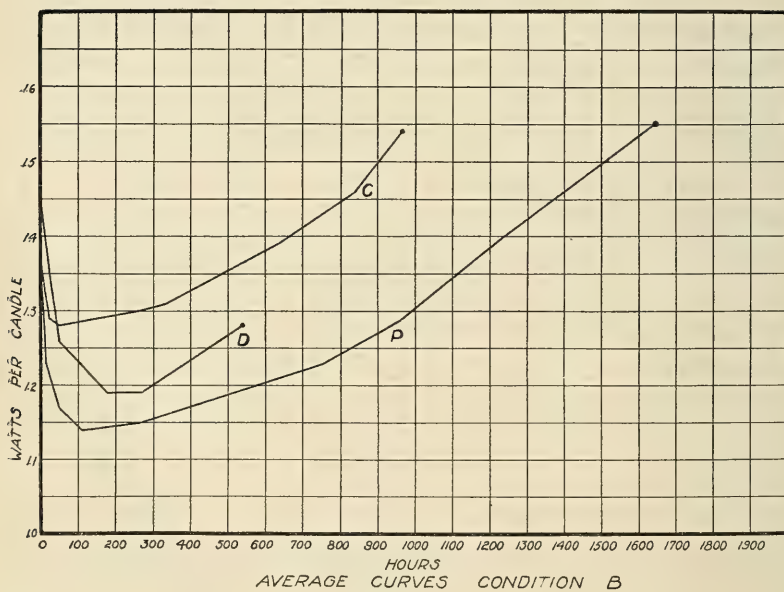


FIG. 24

the *P* lamps decreased to 88 per cent, the *D* lamps to 89 per cent and the *C* lamps to 77 per cent of the initial value.

The curves of average efficiency show the *C* lamp to have the highest watt per candle consumption throughout the tests. Up to about 1100 hours, the *D* lamp gives a poorer efficiency than the *P* lamp, but at this point the curves cross and the *D* lamp gives the better efficiency from that time on. This change in the relative efficiency of the two lamps is due to the greater blackening of the bulb of the *P* lamp.

Bulb Discoloration.—For the purpose of securing a standard by which the discoloration of the different lamps could be compared, a series of 10 carbon lamps was obtained from the Electrical Testing Laboratories of New York. These lamps had been burned for different periods and consequently carbon deposits of different densities were formed on the bulbs; they ranged in intensity from 95 per cent of the original candle-power down to 66.9 per cent. They were numbered from 1/2 to 5 as shown below.

TABLE 3

Lamp No.....	1/2	1	1 1/2	2	2 1/2	3	3 1/2	4	4 1/2	5
Per cent C. P..	95	91.3	86.9	83	78.6	75.3	73	70.5	68.7	

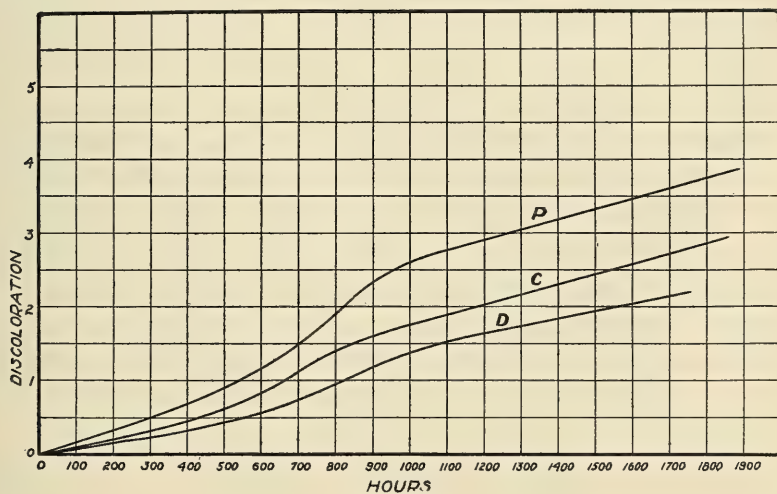


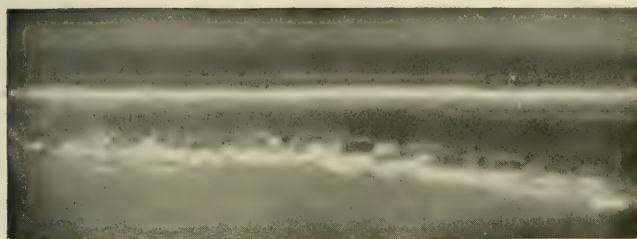
FIG. 25

At intervals throughout the life test, the color of each tungsten lamp was compared with that of the series of carbon lamps, and the number with which it matched in color was noted. In this way the rapidity with which the tungsten lamps blackened could be determined. The lamps did not blacken uniformly over the surface, hence the darkest portion was always chosen for comparison. Fig. 25 shows the results obtained. It is plotted between hours of burning and discoloration and represents the average results of 25 lamps of each kind. The *P* lamp shows the most pronounced discoloration while the *D* lamp shows the lowest. The *P* lamps were decidedly non-uniform in the rapidity with which they blackened. Some of them would be discolored scarcely any after 1000 or 1500 hours' burning, while the others would be as black as the No. 5 carbon lamp. The *C* and *D* lamps seemed to blacken uniformly, so that at any time all of the lamps of either of these types would be discolored approximately the same amount.

In Fig. 26 are microphotographs showing the condition of the filaments after a long period of burning. In each case a new filament is shown for comparison. As might be expected, all three filaments become much roughened and pitted after a period of burning, and decrease somewhat in size, the *D* filament to a considerable extent. Filaments burned upon alternating current are the same in appearance as those burned upon direct current for the same length of time and do not show the segmentation that takes place in tantalum filaments.

A summary of the performance of the lamps on the life and efficiency tests is shown in Table 4. The curves in Fig. 27 and 28 are plotted between "Total cost in cents per candle-power-hour for lamps and energy" as ordinates and "Cost of energy per kilowatt-hour" as abscissas. The curves for condition A are drawn from calculations based upon a 2000-hour test and those for condition B from calculations based upon a 1000-hour test.

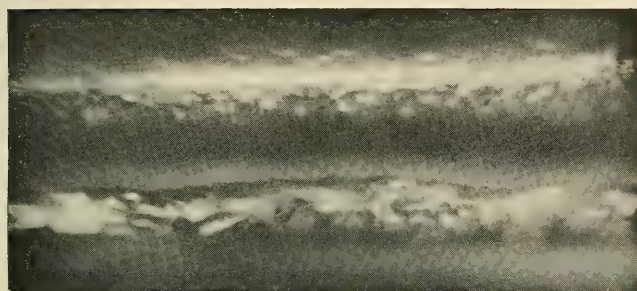
On account of the lower cost of lamp and the fewer burnouts, the *P* lamp gives a considerably lower total cost of operation than the other two. The cost of operating the *D* lamp under condition



New

After burning
1000 hours

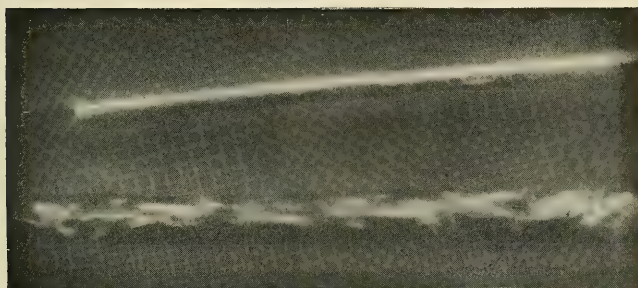
C Filament



New

After burning
1000 hours

D Filament

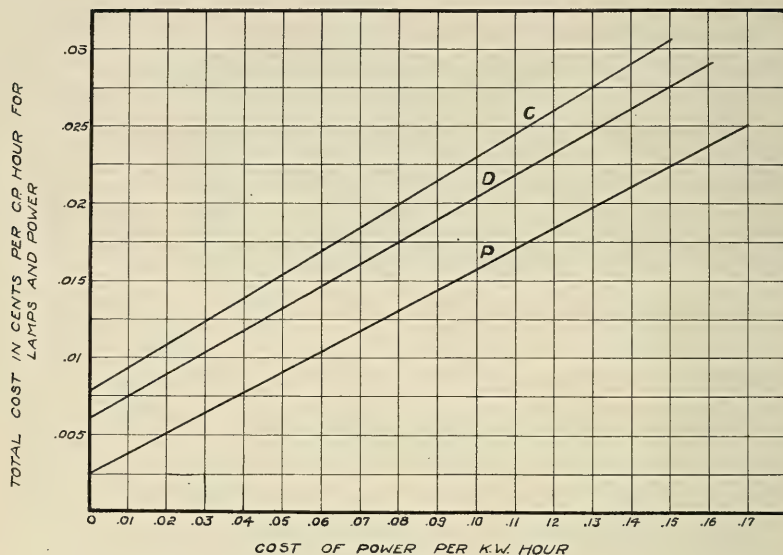


New

After burning
1000 hours

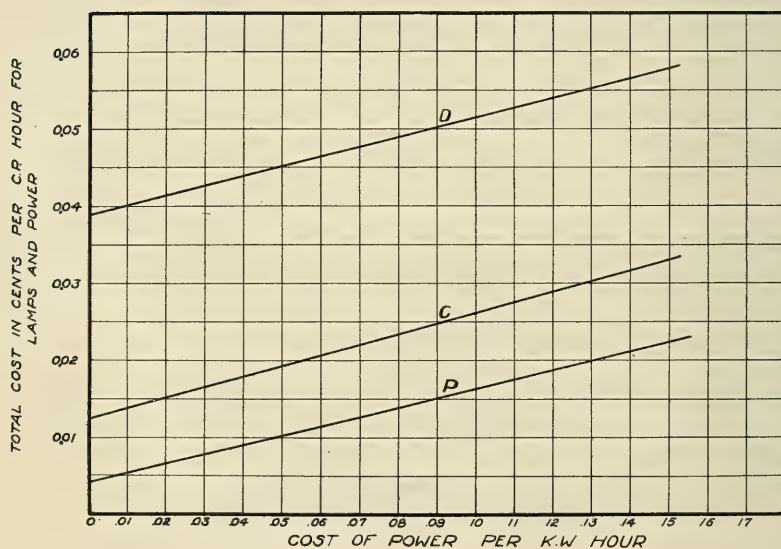
P Filament

FIG. 26



Condition A

FIG. 27



Condition B

FIG. 28

TABLE 4
SUMMARY OF LIFE AND EFFICIENCY TESTS

Lamp Operating Condition	C		D		P	
	A	B	A	B	A	B
Av. Mean Horizontal C. P.						
a. New	19.9	20.6	18.6	19.9	19.9	19.3
b. 1000 hours	18.2		19.7		20.8	20.6
c. 2000 hours	15.0		16.7		191	
Spherical Reduction Factor	.840		.730		.785	
Av. Watts per Lamp	27.5	27.4	28.0	28.0	27.7	27.0
Av. Initial Watts per C. P.	1.36	1.36	1.48	1.44	1.32	1.32
Av. Life in Hours	762	434	1167	153		898
Av. C. P. through Life	18.2	20.2	19.5	22.5	20.9	22.5
Cost Lamps to run 1000 hrs.		\$62.64		\$220.05		\$23.80
" " " 2000 "	\$70.28		\$58.05		\$25.50	
C. P. Hours per Lamp	36,400	20,200	39,000	22,500	41,800	22,500
Total C. P. Hours	910,000	505,000	975,000	562,000	1,045,000	562,000
Kilowatt Hours	1,375	685	1,400	700	1,385	675
Cost of Lamps	\$1.08		\$1.35		\$.85	

B is excessively high on account of the exceedingly short average life of the lamps under this condition; in fact, for power costs below 12 or 13 cents per kilowatt-hour, they are more expensive to operate than ordinary carbon filament lamps.¹

VII. CONCLUSIONS

Comparisons of the durability of filaments made by the colloid, deposition and paste processes are very difficult to make owing to the fact that the three types were all mounted differently. Undoubtedly the manner of mounting a filament has a great effect upon its life, and whether the superior life of one type of lamp is due to the fact that it has a better scheme of mounting or to the fact that the process of manufacture is better, can hardly be decided definitely from these tests. Tests of filaments made by the three processes and mounted in exactly the same way would be necessary to decide this question absolutely. From the tests just

¹ In Engineering Experiment Station Bulletin No. 19 are given the results of tests upon carbon, metallized carbon and tantalum lamps which may be compared with the results given in this bulletin for tungsten lamps. It should be said, however, that the metallized carbon and tantalum lamps used for the tests described in Bulletin No. 19 were manufactured three or more years ago and that lamps of these kinds now manufactured and put upon the market show a considerable improvement over the ones tested.

described, however, the colloid process seems to give a filament that is less durable than the other two. It is true that when tested under condition B, it gave a longer life than did the *D* lamp, but this was because its construction enabled it to withstand vibration better rather than because of the superior quality of the filament. Under condition A where vibration was eliminated and where the scheme of mounting had less effect upon the life, the *D* lamp gave a considerably longer life. The *P* lamp gave a much better life under both conditions of operation than the *C* and *D* lamps. This must be due at least in part to the fact that the filament has better lasting qualities than those made by the other processes. Under condition A, this lamp shows the same superior life as it did under condition B where differences in mounting produce great differences in average life.

Of the three schemes for mounting the filaments, that of the *C* lamp undoubtedly holds the filament more nearly in the desired place for all positions of burning than the other two. While holding it in the proper position, it at the same time holds it loosely enough so that all necessary contraction can take place without putting it under a tension that is likely to cause it to respond readily to vibrations. The principal defects of this scheme of mounting are that it lacks simplicity and that there are a large number of supporting spires that carry off by heat conduction energy that should be radiated in the form of light. For burning in a vertical pendant position or nearly so, the mounting of the filament in the *P* lamp is very good. The filament is held loosely so that contraction can take place without putting it under sufficient tension for vibration to have the serious effect upon it that it does upon the *D* filament. When burning horizontally it sags considerably, often enough to allow it to touch the glass stem supporting it. This at least gives the lamp a poor appearance even if it caused no other bad effects. The mounting of the *D* filament permits almost no distortion of the filament to take place when burning horizontally, but it has the serious fault of holding the filament in tension so that it responds readily to vibrations. The spring suspension of the supporting stem tends

to make worse the very thing that it is intended to prevent. No doubt there would be less trouble from vibration with this style of filament mounting if the stem were rigid. That there would still be bad effects from vibration even if the stem were rigid is proved by the *P* lamp. When a filament section in this lamp, which has a rigid stem, contracted sufficiently to put it under tension, as sometimes happened, it would respond to vibrations when burning under condition B in the same way that the *D* filament did, and then quickly fail. A considerable number of the newer tungsten lamps coming on the market have their filaments mounted under a slight tension, just as in the *D* lamp, but where they are to be subject to vibration, it is doubtful if they will give as good results as more loosely strung filaments would.

These tests show that the performance of tungsten lamps may vary to a surprising degree depending upon the kind of lamps used and upon the conditions under which they are burned. Some lamps will give as high operating cost as the old carbon lamps while burning under certain conditions, whereas other lamps will give good results under those same conditions. Under the best conditions, however, the tungsten lamps now on the market give excellent results. Their efficiency is maintained in a remarkable way and the life is very long, often several times what they are advertised to give.

Breakage in shipment and handling have been reduced to a small fraction of what was common in the early lamps. Only three of the three hundred lamps which were purchased for these tests were received with broken filaments, and although the lamps on some of the tests which have been described were handled dozens of times, almost no trouble was experienced so far as the breakage of filaments was concerned.

The other defect of the early lamps, that of early blackening of the bulbs, seems to have been overcome. Not one of the lamps on the tests showed any early discoloration at all, in fact, not until after about 600 hours of burning did any of the bulbs show an appreciable amount of blackening.

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

- Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print*).
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- Bulletin No. 3.* The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (*Out of print*).
- Bulletin No. 4.* Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.
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BULLETIN NO. 34

TESTS OF TWO TYPES OF TILE-ROOF FURNACES UNDER A WATER-TUBE BOILER

BY

J. M. SNODGRASS



UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

URBANA, ILLINOIS
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ENGINEERING EXPERIMENT STATION

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MAY 1909

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BY J. M. SNODGRASS, ASSISTANT PROFESSOR OF MECHANICAL
ENGINEERING, ENGINEERING EXPERIMENT STATION

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I. INTRODUCTION

1. *Purpose of Tests*

The tests were made for the purpose of comparing boiler performance when operating with two types of furnace roofs.

2. *Two Types of Furnace Roofs*

The essential difference between the two furnace roofs employed consisted in the fact that in one case the tubes of the lower row were completely surrounded by the tile which formed the roof of the furnace, while in the other case the roof tile rested upon the tubes of the lower row, leaving the lower half of the tubes directly exposed to the flames and hot gases arising from the fire bed. This difference and the construction of the two types of roof are shown in Fig. 1, 2, and 3.

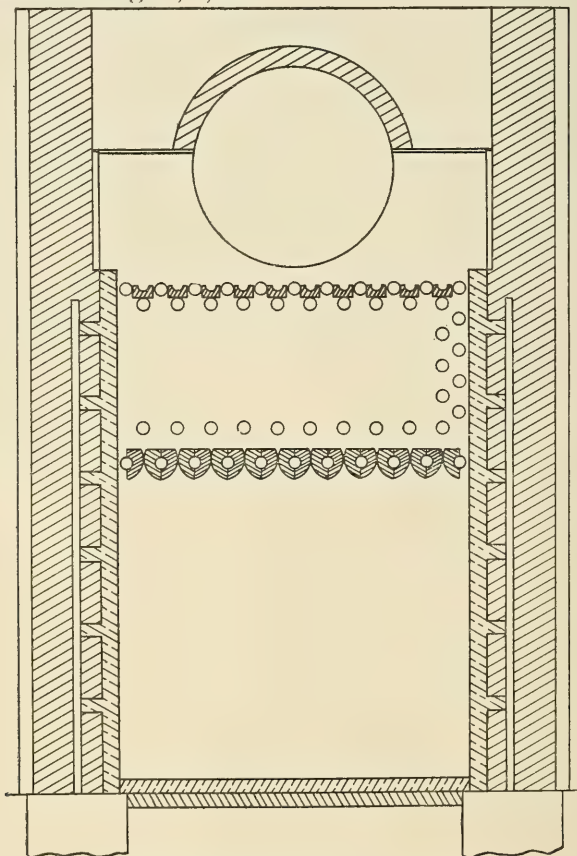


FIG. 1 CROSS-SECTION SHOWING CONSTRUCTION OF
FURNACE ROOF AS MADE FROM C TILE

Fig. 1 shows in cross-section the roof in which the tile used completely encircled the tubes and prevented the flames and hot gases from coming in direct contact with the water-heating surface until they had traveled to the rear end of the furnace roof. This type of roof has been designated as the *C* tile roof.

Fig. 2 shows in cross-section the roof in which the roof tile rested upon the tubes, covering their upper surface only, leaving the lower surface of the tubes to be acted upon directly by the flames and hot gases arising from the fire-bed. This type of roof has been designated as the *T* tile roof. Strictly speaking, this roof would not be considered a tile roof, if, by the term tile roof, is

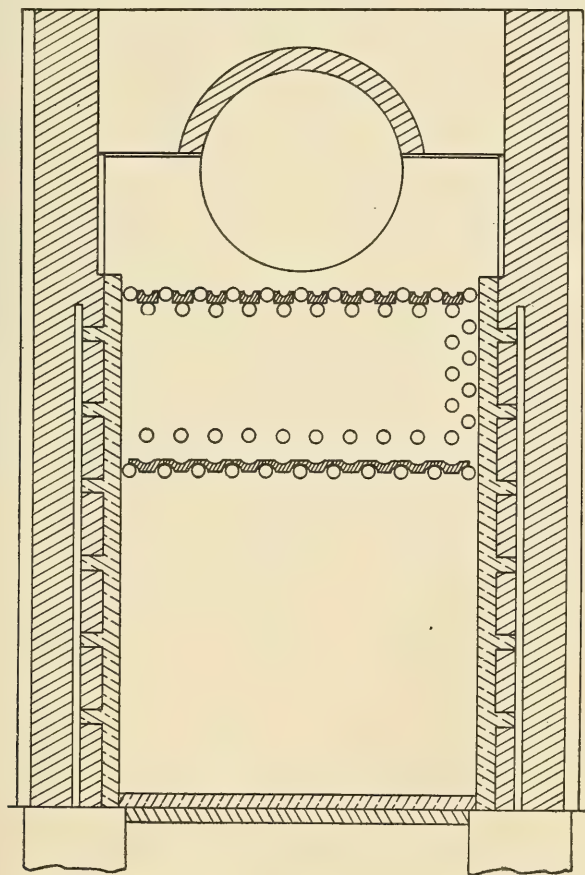


FIG. 2 CROSS-SECTION SHOWING CONSTRUCTION OF FURNACE ROOF AS MADE FROM *T* TILE

meant a roof which presents to the fire a surface composed entirely of tile.

Fig. 3 is a longitudinal section showing the general arrangement of furnace and boiler. This shows the *C* tile roof in position. For the tests with the *T* tile, no changes were made except to remove the *C* tile, as shown in Fig. 3, replacing them with *T* tile. The first two rows of tile, crosswise of the boiler, and immediately back of the front water-leg consisted of *T* tile during all of the tests, as shown in the longitudinal section with the *C* tile roof in place, Fig. 3. These two rows of *T* tile facilitated the cleaning and inspection of the front end of the tubes.

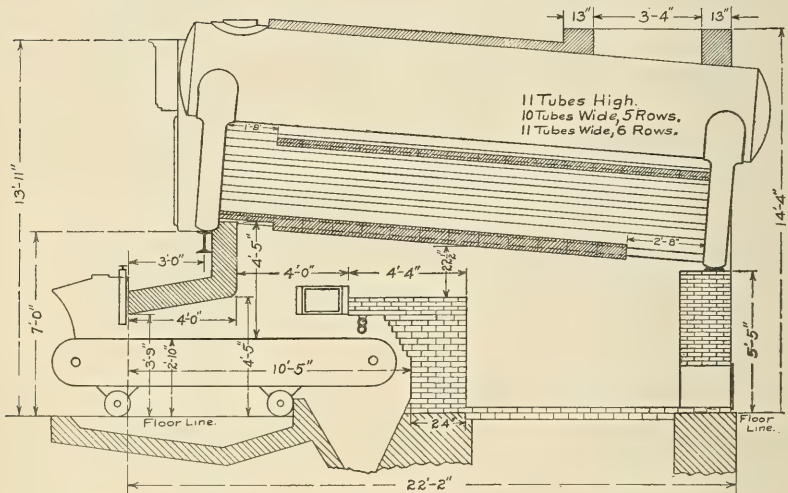


FIG. 3 LONGITUDINAL SECTION SHOWING ARRANGEMENT OF
BOILER AND FURNACE

II. SUMMARY AND CONCLUSIONS

(1) Eight tests were made upon two types of roofs, four with each type.

(2) The minimum capacity developed for any one test was 102 per cent of rated capacity, and the maximum, 106 per cent of rated capacity.

(3) For the tests with the *C* tile roof, the boiler efficiencies varied from 64.4 per cent to 66.3 per cent with an average of 65.6 per cent. For the *T* tile roof tests the efficiencies varied from 67.5 per cent to 69.4 per cent with an average of 68.6 per cent. This shows a gain of 3 per cent in the boiler efficiency in favor of the *T* tile roof.

(4) The gain in water evaporated per pound of combustible is 5 per cent more when using the *T* tile than when using the *C* tile.

(5) The temperatures in the furnace and combustion chamber are from 200° to 400° F. less when using *T* tile than when using *C* tile. This condition should make radiation losses less when the roof is made of *T* tile. Maintenance of furnace, boiler and setting should be easier and less expensive with the *T* tile due to the lower temperatures. Lower flue gas temperatures are obtained when using *T* tile and are particularly of advantage when using induced draft apparatus.

The tests were not of sufficient length or at sufficiently high capacities to furnish data relative to the total life of such furnace roofs or to their relative effect upon boiler maintenance in many particulars. It is not uncommonly believed that with uncovered tubes, as with the *T* tile roof, at high capacities, there is much greater danger of injuring the tubes than with tubes covered, as with the *C* tile roof, and, consequently, greater difficulty in regard to boiler maintenance.

(6) Uniform and satisfactory fire conditions were more easily maintained during the tests with the *T* tile roof than with the *C* tile roof. It is possible that this condition may have been due entirely to other conditions than the difference in roofs.

(7) No smoke was made with the *C* tile roof and only smoke of a comparatively unobjectionable color when using the *T* tile roof. These results were at approximately 100 per cent of

rated capacity. It is probable that the *C* tile roof could have been pushed to considerably higher capacities than the *T* tile roof without producing objectionable smoke.

(8) The *C* tile roof is superior to the *T* tile roof in the matter of smokelessness while the *T* tile roof is superior as regards simplicity, maintenance and efficiency.

III. FUEL

The coal as received was $1\frac{1}{4}$ -inch screenings mined near Danville, Vermilion county, Illinois. In order to make it easier to maintain uniform conditions and to operate easily at 100 per cent rated capacity, or higher if desired, this coal, as it was shoveled from the car, was run over a $\frac{1}{2}$ -inch screen. In this way a large part of the very small coal was removed. The portion of the original coal which would pass through a $\frac{1}{4}$ -inch screen averaged about 38 per cent and approximately this per cent of the coal was removed by screening as described above. On account of the coal being wetter in the cars during inclement weather than at other times, the screening process did not give entirely uniform results. As between the two series of tests, however, there was believed to be no appreciable difference in this respect at the time of conducting the tests.

Proximate chemical analyses of the coal used on each test with the calorific value will be found in Table 5, pp. 17, 18.

IV. EQUIPMENT

The tests were made upon a 210 horse-power water-tube boiler set over a chain grate stoker as shown in Fig. 3. This is the Engineering Experiment Station experimental fuel testing boiler and is similar to the boiler used at the U. S. G. S. testing plant at St. Louis, Missouri, and at Norfolk, Virginia. A number of the principal dimensions, not upon Fig. 3, are given in Table 1.

TABLE 1
DIMENSIONS OF ENGINEERING EXPERIMENT STATION
FUEL TESTING BOILER

Kind of boiler.....	210 H. P. Heine water-tube
Kind of furnace.....	Green chain grate
Width of grate.....	inches 54
Length of grate.....	" 102
Grate surface.....	sq. ft. 38.25
Area of chimney.....	" " 8.7
Height of chimney above grate.....	feet 45.5
Kind of draft.....	Induced
Water heating surface.....	sq. ft. 2027
Number of tubes.	116
Diameter of tubes, outside.....	inches 3.5
Ratio of water heating surface to grate surface,	53.1 to 1

Fig. 4, from a photograph, gives a view of the front of the boiler and of the induced draft apparatus, also the water weighing tanks, ash and coal cars, hoist and scales. The plant was especially designed for test purposes and is equipped with all apparatus ordinarily employed in such work. Descriptions of this plant have appeared in the bulletins of the Engineering Experiment Station in connection with work already reported.*

*University of Illinois Engineering Experiment Station Bulletins No. 15; No. 36.

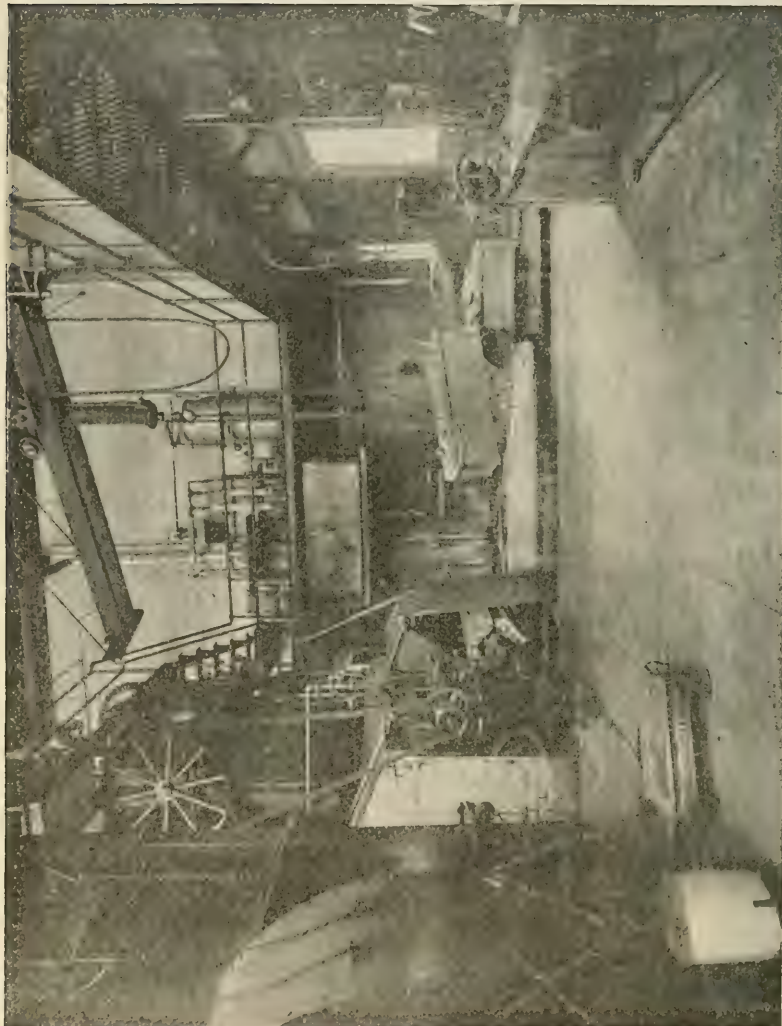


FIG. 4 GENERAL VIEW OF ENGINEERING EXPERIMENT STATION FUEL TESTING PLANT.
210 H. P. HEINE BOILER, WEIGHING TANKS, ASH CAR AND HOIST, INDUCED DRAFT.

V. METHODS OF CONDUCTING THE TESTS

In general the methods as indicated by the A. S. M. E. code for conducting boiler trials were used.

(1) *Preparation*.—Before each series of tests, the boiler was washed out and the upper baffle of *U* tile thoroughly cleaned off. Before the tests with the *C* tile roof, the soot and ashes were removed from the upper side of the roof as thoroughly as possible by using the blower repeatedly from both ends of the boiler. The *T* tile roof was practically clean at the beginning of the tests, having been in use only about 24 hours previous to the first test. The boiler was blown down and the tubes blown off each night before the test of the following day. Fires were built up from the banked fire several hours before the beginning of a test, so that at the start operating conditions were uniform, and the boiler developing approximately its rated capacity.

(2) *Method of Starting and Stopping*.—The alternate method of stopping and starting the tests was used.

(3) *Firing*.—The coal fired was weighed out in lots of 500 lb. and record made both of the time consumed in burning each 500 lb. lot and of the amount of coal consumed during each hour of the test.

The opening between the grate and the lower edge of the gate measured $5\frac{1}{4}$ inches, for all tests, and the fuel bed thus admitted has been called 5 inches thick.

(4) *Feed Water*.—The amount of water fed to the boiler was determined by measuring tanks. The measuring tanks were set upon scales and measured weights were frequently checked by weighing.

(5) *Quality of Steam*.—The quality of the steam was determined with a throttling calorimeter.

(6) *Smoke Records*.—Smoke comparisons were made by means of the Ringlemann scale, No. 1, 2, 3, 4 and 5 representing respectively 20, 40, 60, 80 and 100 per cent of black smoke.

(7) *Flue Gas Samples*.—Flue gas samples were analyzed each hour, an average sample being collected over that interval of time. The sampling apparatus consisted of six $\frac{1}{4}$ -in. sampling

tubes distributed across the uptake. Samples were drawn from a junction box to which all of the sampling tubes were connected. Analyses were made with the Orsat apparatus.

(8) *Flue Temperatures.*—The flue temperatures recorded were taken at the center of the uptake at the same section from which the flue gas samples were drawn.

(9) *Water-back.*—The amount of water used by the water-back was measured by means of a meter which had been calibrated and found reliable over the range at which it worked.

(10) *Temperatures, Pressures and Drafts.*—Temperatures, pressures and drafts were recorded in the usual manner either with direct reading or recording instruments. Observations were in general taken every 20 minutes, although some observations were made at longer or shorter intervals, as seemed desirable in particular cases.

(11) *Furnace and Combustion Chamber Temperatures.*—Furnace and combustion chamber temperatures were taken at four places. These observations were taken hourly for all tests and during some tests at 20-minute intervals. Thermo-electric couples were employed which were capable of registering temperatures to about 2400° F. to 2500° F. before breaking down. Four such couples were used, two of which broke down during the tests, due to exposure to excessive temperatures. With four couples in service the four observations were taken consecutively during an interval of time amounting to one minute or less. When only two couples were in service they had to be transferred, and the time required to obtain the four observations amounted to several minutes. The couples used were compared with each other and with other pyrometers, although complete and satisfactory calibrations were not made. As compared with each other, the couples were quite uniform; while as compared with other pyrometers, the variation was from 0° to 50° F. All of the furnace and combustion chamber temperatures given are the same as those recorded, no corrections having been applied. They can be used for purposes of comparison as between different tests or series of tests or between temperatures at different parts of the setting. It is believed that most of the temperatures as recorded are correct within a variation of 50° F., that is, within either 25° above or below the recorded observation.

VI. DISCUSSION

(1) *Uniformity of Conditions.*—Throughout all tests an effort was made to maintain conditions uniform except as such conditions might be affected by the two kinds of tile roof being used.

In two important items, draft and the amount of unburned fuel carried away in the refuse, there was some difference as between different tests.

The average draft in the uptake was 0.29 in. of water for the first test with the *C* tile, 0.43 in. of water for the second test and 0.35 in. for the other two tests. The lowest average draft for any test with the *T* tile was 0.31 in. of water, the highest 0.36 in., and 0.35 in. was the average draft for each of the other two tests.

The unburned fuel carried away in the ash and refuse was higher in the tests with the *C* tile than in those with the *T* tile. For the tests with the *C* tile the per cent of carbon in the ash and refuse varied from 30 per cent to 21 per cent, while for the tests with the *T* tile the corresponding figures were 22 per cent and 11 per cent. The better fire-bed conditions, indicated by the lower percentage of carbon in the ash for the second series of tests may have been due in part to better screened coal during the later tests, and to the fact that the men handling the boilers were becoming better accustomed to the work. Before any of the tests which have been reported were made, however, two preliminary tests of 10 hours each were run upon the two days preceding the first test reported. Throughout the tests no particular difficulty was experienced in maintaining apparently uniform conditions and operating at the capacity determined. The matter of coal screening is considered in the paragraph concerning fuel.

(2) *Evaporation and Efficiency.*—Table 2 presents results as to evaporative performance and efficiency. The equivalent evaporation per pound of combustible varies from 9.57 lb. to 9.88 lb. of water with the *C* tile roof in use and from 10.12 to 10.34 lb. of water with the *T* tile roof in use. The average for the *C* tile roof test is 9.76 lb. and for the tests with the *T* tile, 10.24 lb., an increase of 5 per cent for the *T* tile roof over the *C* tile roof. The boiler and furnace efficiency (not including the grate) shows an average efficiency of 65.6 per cent for the *C* tile tests and

68.6 per cent for the *T* tile tests, an increase of 3 per cent in the boiler efficiency. Corresponding figures based upon equivalent evaporation per pound of dry coal fired and upon plant efficiency, which include the action of the grate, show the results to have been about 8 per cent better in the case of the *T* tile tests than in the case of the *C* tile tests.

TABLE 2
EVAPORATIVE PERFORMANCE AND EFFICIENCY
COMPARISON BETWEEN *C* AND *T* TILE-ROOF TESTS

Test No.	Equivalent Evaporation from and at 212° F. pounds				Efficiency per cent			
	Per Pound of Combustible		Per Pound of Dry Coal		Boiler and Furnace		Boiler, Furnace and Grate	
	<i>C</i>	<i>T</i>	<i>C</i>	<i>T</i>	<i>C</i>	<i>T</i>	<i>C</i>	<i>T</i>
1	9.88	10.23	7.48	8.07	66.3	68.6	60.5	65.4
2	9.57	10.34	7.56	8.37	64.4	69.4	61.5	67.5
3	9.78	10.12	7.82	8.37	65.9	67.5	62.0	66.1
4	9.80	10.26	7.63	8.31	65.8	68.8	61.9	67.3
Average	9.76	10.24	7.62	8.28	65.6	68.6	61.5	66.6

(3) *Combustible Consumed*.—Item 30, “total combustible consumed,” was calculated by subtracting from the total dry coal fired, the ash as determined by chemical analysis and the combustible carried away in the refuse. In all calculated items in which combustible enters as a factor, this value has been used. Boiler efficiency values in particular are affected by the method in which the total combustible is computed.

(4) *Water-back*.—The amount of heat taken up by the water-back has not been considered in calculating the results. If all of the heat taken up by the water-back were assumed to have been returned to the boiler in the feed water without affecting conditions otherwise, the efficiencies so calculated would have been considerably higher. Table 3 gives a comparison of the efficiencies as calculated, and those calculated on the assumption that the heat taken up by the water-back was utilized by the boiler.

Had the assumption been made that a portion only of the heat taken up by the water-back should be credited to the boiler, the values for efficiency would have been found somewhere between the values given.

TABLE 3

COMPARISONS CONCERNING EVAPORATIVE PERFORMANCE AND EFFICIENCY
WHEN CREDITING THE BOILER WITH ALL OF THE HEAT TAKEN
UP BY THE WATER-BACK

	Test No.	Equivalent Evaporation from and at 212° F. per pound of Combustible, pounds		Efficiency of Boiler and Furnace (not including grate) per cent	
		No Credit Given Boiler for Heat Taken up by Water-back	Crediting All Heat Taken Up by Water-back to Boiler	No Credit Given Boiler for Heat Taken up by Water-back	Crediting All Heat Taken Up by Water-back to Boiler
<i>C</i> Tile Roof	1	9.88	10.16	66.3	68.2
	2	9.57	9.89	64.4	66.5
	3	9.78	10.07	65.9	67.9
	4	9.80	10.08	65.8	67.7
	Aver.	9.76	10.05	65.6	67.6
<i>T</i> Tile Roof	1	10.23	10.45	68.6	70.1
	2	10.34	10.52	69.4	70.6
	3	10.12	10.53	67.5	68.9
	4	10.26	10.50	68.8	70.5
	Aver.	10.24	10.45	68.6	70.0

(5) *CO₂ in Flue Gases.*—The average CO₂ content for all tests with the *C* tile roof was 6.8 per cent and for the tests with the *T* tile roof 7.5 per cent. CO was either not found in the flue gas or found only in small amounts. The lower CO₂ content for the *C* tile roof tests may have been due to poorer fire-bed conditions or to greater leakage of air through the setting during those tests.

(6) *Smoke.*—Except for the first test with the *C* tile roof, during which regular observations were not made, smoke observations were made at 10-minute intervals except as darkness prevented. Irregular observations for the first test gave “No smoke” for that test.

During the three tests upon which smoke observations were made with the *C* tile roof, 161 observations were recorded. One of these recorded smoke No. 1; 7 recorded smoke No. $\frac{1}{2}$; and 153, no smoke. This is considered as smokeless operation.

During the four tests with the *T* tile roof, 233 observations were recorded. One observation of No. 2 smoke was made, which was the maximum recorded. As shown in Table 5, page 19, the average smoke recorded varied from 9 per cent to 17 per cent for the four tests. These percentages correspond approximately to No. $\frac{1}{2}$ and No. 1 smoke by the Ringlemann scale.

The operation with the *C* tile roof was smokeless and higher capacities could doubtless have been obtained without trouble from this source. With the *T* tile roof, the operation as to smokelessness was quite satisfactory, no smoke of a blackness greater than No. 2 being recorded, and the average for all tests being well under No. 1. It was evident that had higher capacities been demanded, trouble with black smoke might have resulted.

(7) *Furnace, Combustion Chamber, Flue Temperatures.*—Table 4 presents the average temperatures as observed at four points in the combustion space and in the flue for each test, also averages for the four tests made with each type of roof.

It will be noted that the temperatures are uniformly lower for the *T* tile roof than for the *C* tile roof, the greatest average difference being 371° at a point in the combustion chamber.

Fig. 5 indicates the location of the openings for the insertion of the thermo-couples and the flue gas pyrometer. The couples extended in all cases about 14 in. into the furnace, measuring from the inside of the setting.

TABLE 4
TEMPERATURES IN FURNACE, COMBUSTION CHAMBER AND FLUE

Test No.	Temperatures—Degrees F									
	Pyrometer No. 1 In Furnace		Pyrometer No. 2 Over Bridge-wall		Pyrometer No. 3 Forward Part of Combustion Chamber		Pyrometer No. 4 Rear Part of Combustion Chamber		Pyrometer No. 5 In Uptake	
	<i>C</i>	<i>T</i>	<i>C</i>	<i>T</i>	<i>C</i>	<i>T</i>	<i>C</i>	<i>T</i>	<i>C</i>	<i>T</i>
1	2052	1893	2177	1873	2023	1636	1677	1409	549	496
2	2086	1870	2061	1830	1861	1625	1534	1418	565	484
3	2073	1869	2202	1845	2063	1530	1721	1325	563	458
4	2053	1902	2164	1855	1923	1595	1636	1384	556	432
Average	2066	1883	2151	1851	1968	1597	1642	1384	558	468
Difference	183		300		371		258		90	

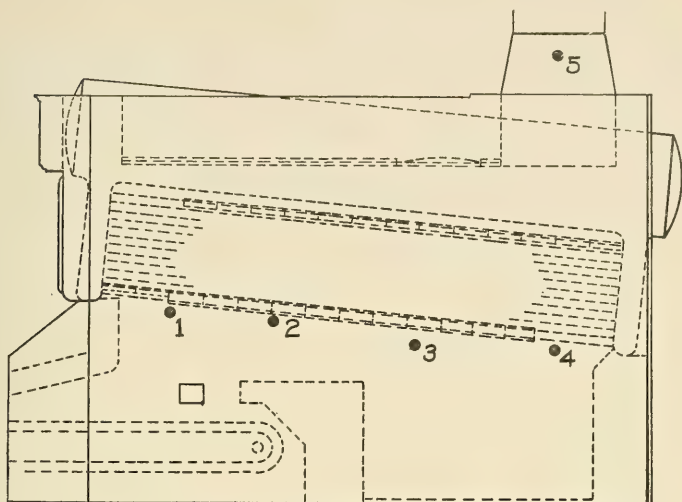


FIG. 5 SHOWING LOCATION OF HOLES FOR INSERTION
OF THERMO-COUPLES AND FLUE-GAS PYROMETER

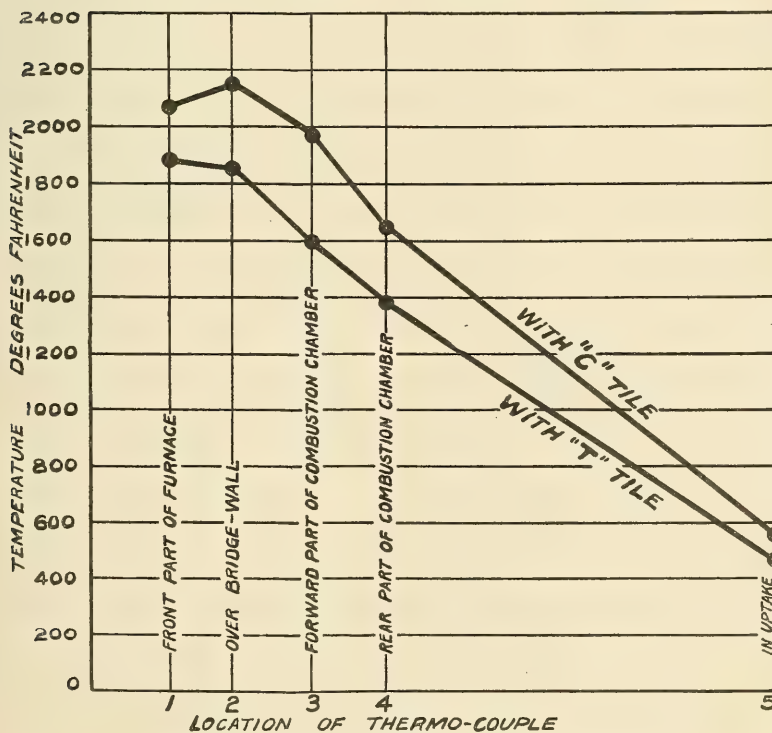


FIG. 6 AVERAGE TEMPERATURES FOR TESTS

In Fig. 6, there have been plotted the average values for all observations taken at the different points for each series of tests. The abscissæ represent approximately the distances of the points of observation from the front of the furnace.

The highest temperature recorded was 2450° F. One thermocouple was melted down and destroyed shortly after an observation of 2350° had been made from it. The breaking down temperature was not noted. All temperature observations were made at regular intervals. The fire at the time of making the 2450° observation and at the time of destroying the couple above referred to was apparently as hot as at any other time during the tests. During the *C* tile-roof tests, the furnace seemed to reach these temperatures a number of times. During the *T* tile-roof tests the temperatures were at all times considerably lower, the maximum temperature recorded being 2000° F.

VII. DATA AND RESULTS

Table 5 gives the principal data and results for the eight tests. Fig. 7 presents a graphical log for one of the tests with *C* tile roof and Fig. 8 a similar log for one of the tests with the *T* tile.

TABLE 5 DATA AND RESULTS
Comparative Tests with *C* and *T* Tile-Roof Furnaces

A.S.M.E. Code No.	Test Number	<i>C</i> Tile-Roof Tests				<i>T</i> Tile-Roof Tests			
		1	2	3	4	1	2	3	4
1	Date of Trial	Dec. 24, 1908	Dec. 29, 1908	Dec. 30, 1908	Dec. 31, 1908	Jan. 11, 1909	Jan. 12, 1909	Jan. 13, 1909	Jan. 14, 1909
2	Duration of Trial (hours)	10	10	10	10	10	10	10	10
11	AVERAGE PRESSURES								
	Steam pressure by gauge, lbs. per sq. in.....	139	138	142	141	139	141	141	141
12	Force of draft between damper and boiler, inches of water.....	.29	.43	.35	.35	.35	.31	.35	.36
13	Force of draft in furnace, inches of water.....	.170	.165	.179	.160	.145	.124	.116	.130
15	AV. TEMPERATURES								
	Of external air, degrees.....	46	44	42	22	12	17	22	35
16	Of fireroom, degrees...	68	70	66	65	64	71	74	72
20	Of feed water entering boiler, degrees.....	56	57	57	56	55	55	55	55
21	Of escaping gases from boiler, degrees	549	565	563	556	496	484	458	432
	FUEL								
25	Weight of coal as fired, lb.....	11149	11000	11102	11092	10882	10340	10058	10438
26	Percentage of moisture in coal, percent	11.27	11.00	12.13	12.84	12.78	12.72	12.60	12.25
27	Total weight of dry coal consumed, lb...	9893	9790	9755	9668	9491	9025	8791	9159
28	Total ash and refuse, lb.....	2313	1721	1853	1860	1654	1376	1346	1374
30	Total combustible consumed, lb.....	7489	7737	7802	7532	7490	7299	7270	7417
31	Percentage of ash and refuse in dry coal, per cent.....	23.38	17.58	19.00	19.24	17.43	15.25	15.31	15.00
	PROXIMATE ANALYSIS OF COAL AS FIRED								
32	Fixed Carbon, percent	35.66	36.85	37.06	36.53	35.30	36.09	37.02	35.17
33	Volatile matter, per cent.....	37.91	36.83	37.71	35.62	36.83	36.55	36.73	37.52
34	Moisture, per cent.....	11.27	11.00	12.13	12.84	12.78	12.72	12.60	12.25
35	Ash, per cent.....	15.16	15.32	13.10	15.01	15.09	14.64	13.65	15.06
36	Sulphur, separately determined, percent	3.51	5.24	4.03	4.10	4.14	4.29	3.79	4.72
43	Moisture in air dry sample, per cent.....	3.66	4.81	3.91	4.38	4.89	5.29	6.27	5.80
	ANALYSIS OF ASH AND REFUSE								
44	Carbon, per cent.....	30.81	21.31	26.92	25.31	21.71	15.45	10.96	12.39
45	Earthy matter, per cent.....	69.19	78.69	73.08	74.69	78.29	84.55	89.04	87.61

TABLE 5 DATA AND RESULTS

Comparative Tests with *C* and *T* Tile-Roof Furnaces

A.S.M.E. Code No.		<i>C</i> Tile-Roof Tests				<i>T</i> Tile-Roof Tests			
		1	2	3	4	1	2	3	4
	FUEL PER HOUR								
46	Dry coal consumed per hour, lb.....	989.3	979.0	975.5	966.8	949.1	902.5	879.1	915.9
48	Dry coal per square foot of grate surface per hour, lb.....	25.89	25.63	25.54	25.31	24.85	23.63	23.01	23.98
	CALORIFIC VALUE OF FUEL								
50	Calorific value by oxygen calorimeter, per lb. of dry coal, B. t. u	11935	11883	12194	11905	11911	11972	12223	11923
51	Calorific value by oxygen calorimeter per lb. of combustible, B. t. u	14394	14354	14331	14381	14403	14384	14485	14393
54	QUALITY OF STEAM Percentage of moisture in steam, per cent..	1.13	1.06	1.20	1.16	1.06	1.12	1.18	1.13
	WATER								
57	Total weight of water fed to boiler, lb.....	61687	61759	63702	61524	63772	62882	61279	63370
58	Equivalent water fed to boiler from and at 212°, lb.....	74598	74610	76997	74419	77185	76125	74190	76716
59	Water evaporated, corrected for quality of steam, lb.....	61175	61277	63141	61001	63275	62366	60746	62844
60	Factor of evaporation..	1.20930	1.20808	1.20870	1.20960	1.21032	1.21060	1.21070	1.21060
61	Equivalent water evaporated into dry steam from and at 212° (Item 59 × Item 60), lb.....	73979	74028	76319	73787	76583	75500	73545	76079
	WATER PER HOUR								
62	Water evaporated per hour, corrected for quality of steam, lb.....	6117.5	6127.7	6314.1	6100.1	6327.5	6236.6	6074.6	6284.4
63	Equivalent evaporation per hour from and at 212°, lb.	7397.9	7402.8	7631.9	7378.7	7658.3	7550.0	7354.5	7607.9
64	Equivalent evaporation per hour from and at 212° per square foot of water-heating surface, lb.....	3.65	3.65	3.77	3.64	3.78	3.72	3.63	3.75
	HORSE-POWER								
65	Horse-power developed. (34½ lbs. of water evaporated per hour into dry steam from and at 212°, equals one horse-power), H. P..	214.4	214.6	221.2	213.9	222.0	218.8	213.2	220.5
66	Builders' rated horse-power' H. P.	210	210	210	210	210	210	210	210
67	Percentage of builders' rated horse-power developed, per cent.....	102	102	105	102	106	104	102	105

TABLE 5 DATA AND RESULTS

Comparative Tests with *C* and *T* Tile-Roof Furnaces

A.S.M.E. Code No.		<i>C</i> Tile-Roof Tests				<i>T</i> Tile-Roof Tests			
		1	2	3	4	1	2	3	4
68	ECONOMIC RESULTS Water apparently evaporated under actual conditions per pound of coal as fired. (Item 57 ÷ Item 25), lb.	5.53	5.61	5.74	5.55	5.86	6.08	6.09	6.07
69	Equivalent evapora- tion from and at 212° per pound of coal as fired. (Item 61 ÷ Item 25), lb.	6.64	6.73	6.87	6.65	7.04	7.30	7.41	7.29
70	Equivalent evapora- tion from and at 212° per pound of dry coal. (Item 61 ÷ Item 27), lb.	7.48	7.56	7.82	7.63	8.07	8.37	8.37	8.31
71	Equivalent evapora- tion from and at 212° per pound of combustible. (Item 61 ÷ Item 30), lb.	9.88	9.57	9.78	9.80	10.23	10.34	10.12	10.26
72	EFFICIENCY Efficiency of the boiler; heat absorbed by the boiler per lb. of combustible divided by the heat value of one lb. of com- bustible, per cent.	66.28	64.38	65.92	65.79	68.56	69.45	67.45	68.83
73	Efficiency of boiler, including the grate; heat absorbed by the boiler, per lb. of dry coal, divided by the heat value of one lb. of dry coal, per cent.	60.51	61.46	61.97	61.92	65.43	67.49	66.10	67.28
76	COST OF EVAPORA- TION Cost of fuel used for evaporating 1,000 lbs. of water from and at 212°, with coal at \$1.00 per ton of 2,000 lb.	.0753	.0743	.0728	.0752	.0710	.0685	.0675	.0686
77	SMOKE OBSERVATIONS Percentage of smoke as observed, per cent.		0.	0.	1.	9.	11.	13.	17.
84	ANALYSIS OF THE DRY GASES Carbon dioxide (CO ₂), per cent.	7.5	5.1	7.7	7.0	6.7	7.7	7.7	7.9
85	Oxygen (O), per cent. ..	11.7	14.9	11.6	12.8	13.1	11.7	11.8	11.5
86	Carbon monoxide (CO), per cent.	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88	Nitrogen (by differ- ence) (N), per cent. ..	80.7	80.0	80.7	80.2	80.2	80.6	80.5	80.6

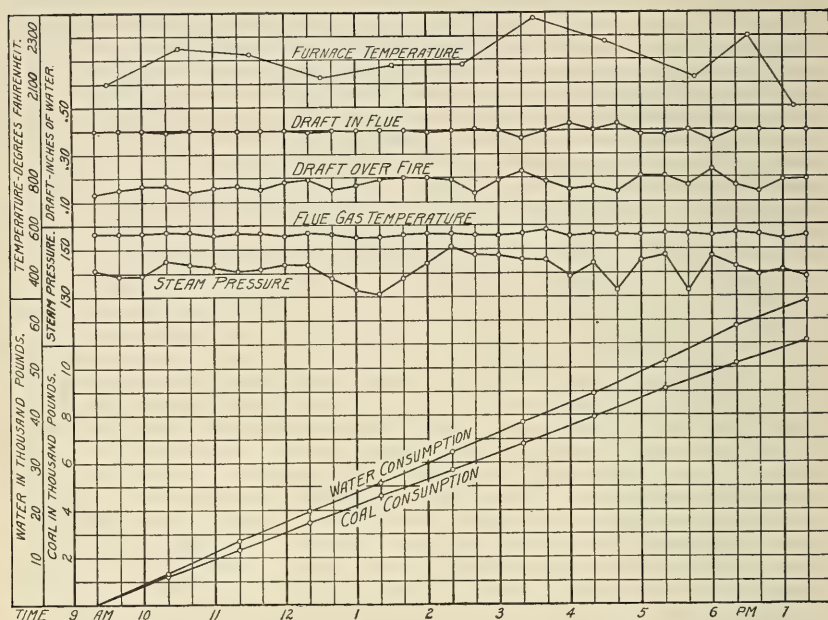


FIG. 7 GRAPHICAL LOG FOR TEST NO. 3, C TILE

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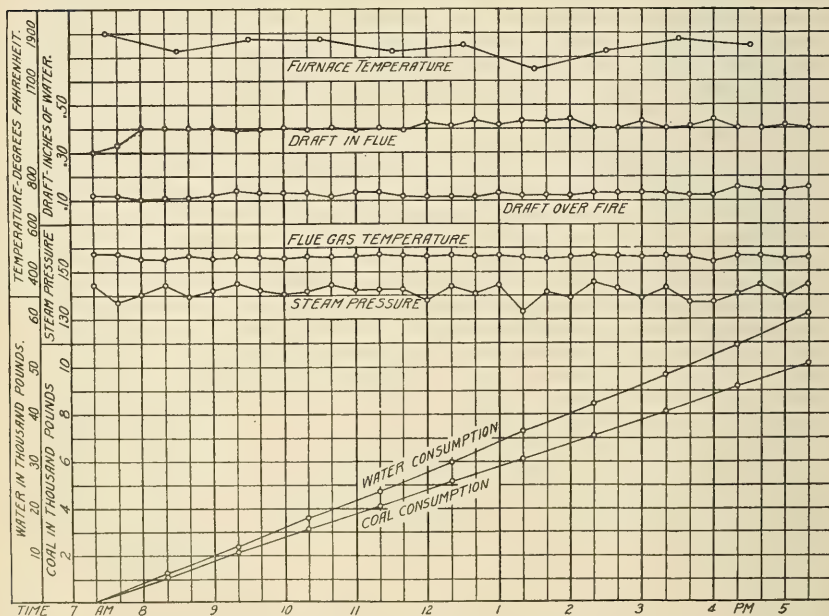


FIG. 8 GRAPHICAL LOG FOR TEST NO. 3, T TILE

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

- Bulletin* No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print*).
- Circular* No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905. (*Out of print*)
- Bulletin* No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. (*Out of print*).
- Circular* No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906. (*Out of print*).
- Circular* No. 3. Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907, by L. P. Breckenridge and Paul Diserens. 1909.
- Bulletin* No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (*Out of print*).
- Bulletin* No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.
- Bulletin* No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906. (*Out of print*).
- Bulletin* No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906. (*Out of print*).
- Bulletin* No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906. (*Out of print*).
- Bulletin* No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906. (*Out of print*).
- Bulletin* No. 9. An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906 (*Out of print*).
- Bulletin* No. 10. Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print*).
- Bulletin* No. 11. The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907. (*Out of print*).
- Bulletin* No. 12. Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print*).
- Bulletin* No. 13. An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.
- Bulletin* No. 14. Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print*).
- Bulletin* No. 15. How to Burn Illinois Coal without Smoke, by L. P. Breckenridge. 1908.
- Bulletin* No. 16. A Study of Roof Trusses, by N. Clifford Ricker. 1908.
- Bulletin* No. 17. The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1908. (*Out of print*).
- Bulletin* No. 18. The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1908.
- Bulletin* No. 19. Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908. (*Out of print*).
- Bulletin* No. 20. Tests of Concrete and Reinforced Concrete Columns, Series of 1907, by Arthur N. Talbot. 1908. (*Out of print*).
- Bulletin* No. 21. Tests of a Liquid Air Plant, by C. S. Hudson and C. M. Garland. 1908.
- Bulletin* No. 22. Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. 1908.
- Bulletin* No. 23. Voids, Settlement and Weight of Crushed Stone, by Ira O. Baker. 1908.
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- Bulletin* No. 27. Tests of Brick Columns and Terra Cotta Block Columns, by Arthur N. Talbot and Duff A. Abrams. 1909.
- Bulletin* No. 28. A Test of Three Large Reinforced Concrete Beams, by Arthur N. Talbot. 1909.
- Bulletin* No. 29. Tests of Reinforced Concrete Beams: Resistance to Web Stresses, Series of 1907 and 1908, by Arthur N. Talbot. 1909.
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- Bulletin* No. 34. Tests of Two Types of Tile Roof Furnaces under a Water-tube Boiler, by J. M. Snodgrass. 1909.

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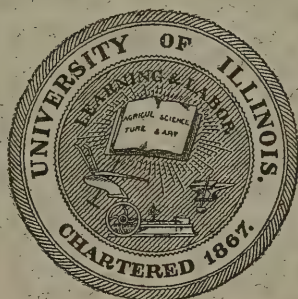
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BULLETIN NO. 35

A STUDY OF BASE AND BEARING PLATES FOR COLUMNS AND BEAMS

BY

N. CLIFFORD RICKER



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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 35

JULY 1909

A STUDY OF BASE AND BEARING PLATES
FOR COLUMNS AND BEAMS

BY N. CLIFFORD RICKER, PROFESSOR OF ARCHITECTURE

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I. INTRODUCTION

The primary object of this study has been to produce a series of accurate formulas and tables for the different forms and materials of base and bearing plates. These formulas are required to be as simple and as easily applied as possible and to be in accordance with the local building ordinances of the larger cities in the United States.

A secondary purpose has been to devise a similar series of formulas based on the common theory of the fracture of such plates and to check the accuracy of these common formulas by experimental tests of a series of plates designed in accordance with such formulas. A number of typical plates were so designed and tested in 1907 by Mr. C. R. Dick, B. S. in Architectural Engineering, and the results were discussed in his thesis.

Up to the present time, very little study of theory and no experimental research appear to have been devoted to these plates. Even the German writers usually give incorrect theories with formulas based thereon, formulas which give erroneous dimensions of base plates.

II. LIMIT OF SAFE PRESSURE OF PLATE ON MASONRY

The maximum safe pressure of the plate on the masonry beneath it varies greatly, according to the nature and the resistance of this material; the requirements of the city building ordinances also differ considerably for the same kind of masonry. These requirements seem to be based upon local customs and not on actual experimental tests. Examples of such maximum safe pressures are here quoted from the ordinances of New York, Chicago and Washington, D. C., selected as representative cities, and these are further compared with the values given in Kidder's Pocket Book. (Table 1.)

Therefore this maximum safe pressure of the plate on masonry appears to vary between 70 and 1000 pounds per square inch, the larger value being allowed for truly dressed large blocks of stone. The value to be employed must be taken in accordance with the local building ordinance.

TABLE 1

Safe Pressures on Masonry in Pounds per Square Inch

<i>Masonry</i>	<i>N. Y.</i>	<i>Chicago</i>	<i>Wash'ton</i>	<i>Kidder</i>
Granite .....	.....	173.61	1000-2400	1000
Limestone .....	.....	173.61	700-2300	.....
Sandstone .....	.....	173.61	400-1600	400-700
Dimension stone, rough....	.....	138.89	.....	.....
Rubble in portland cement..	138.89	.....	140.	150-200
Rubble in natural cement...	111.11	.....	111.	.....
Rubble in cement and lime.	97.22	.....	97.	.....
Rubble in lime.....	94.44	.....	70.	.....
Brickwork in portland cement.	208.33	173.61	250.	150-250
Brickwork in natural cement..	.....	125.	208.	.....
Brickwork in cement and lime.	159.72	.....	160.	.....
Brickwork in lime.....	111.11	90.28	111.	100-120
Concrete in portland cement	208.33	173.61	208-230	200.
Concrete in natural cement.	111.11	.....	111-125	.....

III. MAXIMUM SAFE FIBER STRESS IN METAL OF PLATE

This maximum fiber stress in pounds per square inch occurs at either top or bottom of a plate of uniform thickness, or at the bottom of a cast-iron plate of tapered thickness. It must not exceed the intensities given in the following table, which are almost uniformly adopted throughout the United States.

TABLE 2

Maximum Safe Fiber Stress in Plates

<i>Metal</i>	<i>N. Y.</i>	<i>Chicago</i>	<i>Wash'ton</i>	<i>Kidder</i>
Steel, compression.....	16 000	16 000	16 000	16 000
Steel, tension.....	16 000	16 000	16 000	16 000
Wrought Iron, compression....	12 000	12 000	12 000	12 000
Wrought Iron, tension.....	12 000	12 000	12 000	12 000
Cast Iron, compression.....	16 000	10 000	16 000	.....
Cast Iron, tension.....	3 000	2 500	3 000	.....

Evidently the maximum tensile stress in cast-iron permitted in Chicago might safely be increased from 2500 to 3000 pounds per square inch, which is permitted in about one-half the cities in the United States.

IV. COMMON FORMULAS

The ordinary formulas for base plates are usually empirical (Kidd) or they are otherwise based on the theory that the line of fracture of a base plate is a straight line tangent to the exterior of the foot of the column standing on the plate (Kohnke). In accordance with this theory, a series of formulas was deduced and later published in the Handbook of the Chicago Architects' Business Association. The essential formulas are the following:

A. For Steel Plates of Uniform Thickness

Let p = maximum safe pressure of plate on masonry in lb. per sq. in.

k = perpendicular distance in inches from column to edge of plate.

t = thickness of plate required, in inches.

(a) For square plates (Fig. 1)

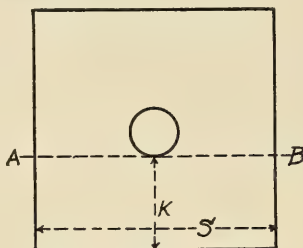


FIG. 1

The line AB (Fig. 1) is the theoretical fracture line.

Then
$$t = \frac{k}{40} \sqrt{\frac{p}{10}} \quad (1)$$

(b) For octagonal plates (Fig. 2)

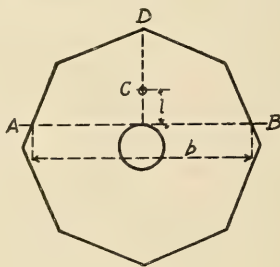


FIG. 2

The segment ADB may be divided into triangles, when its center of gravity C is easily found by graphical methods. (See Graphic Statics.)

B. For Cast-iron Plates of Tapered Thickness

Such plates are of uniform thickness only beneath the end of a column or beam, and are flat on the under side, but are beveled off on top from column to edge of the plate. These edges are usually made at least $\frac{3}{8}$ -in. thick, and a good rule is to make the edge one-fourth the thickness at the middle. These formulas are deduced for sharp edges or a trapezoidal fracture section, and they are therefore only approximate for plates with thick edges.

(a) For square plates (Fig. 4)

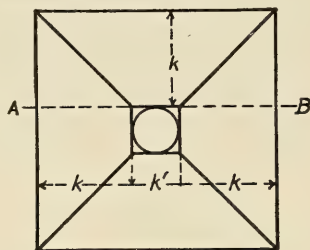


FIG. 4

Let k = projection of the edge of the plate outside the column, measured in inches and perpendicular to the edge.

k' = side in inches of square on top of plate and tangent to column.

The line of fracture AB is parallel to a side.

The thickness in inches of plate at middle is then given by the formula

$$t = \frac{k}{50} \sqrt{\frac{6 p (k + \frac{k'}{2})}{k + k'}} \quad (4)$$

(b) For octagonal plates (Fig. 5)

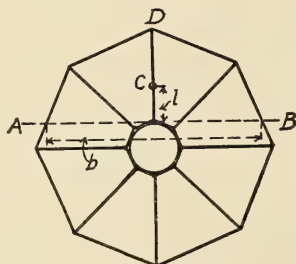


FIG. 5

In the manner already explained for the octagonal steel plate may be found the area a of the segment ADB , its center of gravity C , and the distance l .

The thickness in inches at the middle is then approximately

$$t = \frac{1}{50} \sqrt{\frac{12 a p l}{b}} \quad (5)$$

(c) For circular plates (Fig. 6)

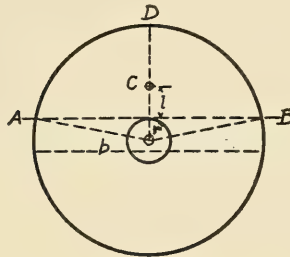


FIG. 6

As for circular steel plates:

$$a = \frac{A \beta}{360} - \frac{bR}{2} = \text{area in square inches of segment } ADB.$$

$$l = \frac{b^3}{12 a} - R = \text{perpendicular distance in inches from } C \text{ to line}$$

AB . The actual fracture section lying between a very flat hyperbola and its chord, a parabola may be substituted therefor without material error.

The thickness at middle is given by the formula

$$t = \frac{1}{50} \sqrt{\frac{35 a p l}{8 b}} = \frac{1}{23.9} \sqrt{\frac{a p l}{b}} \quad (6)$$

V. RESULTS OF TESTS BY C. R. DICK

Employing the preceding formulas, Mr. C. R. Dick designed in 1907 a series of square, octagonal and circular plates of steel and of cast iron, and afterwards tested them in the testing laboratory of the University.

Each plate had a bottom area of 400 sq. in. and transmitted the very moderate safe pressure of 50 lb. per sq. in., making a total maximum safe pressure of 20 000 lb. for the entire plate. The thickness of each plate was made such that the maximum safe fiber stress in the fracture section produced by this maximum safe pressure should not exceed 16 000 lb. for steel or 2500 lb. for cast iron in tension, as required by the Chicago ordinance.

The distribution of the pressure of the plate uniformly over the lower surface required some form of elastic cushion between the plate itself and the very rigid bed of the testing machine. A cushion was composed of several folded blankets, a folded woollen comfortable and two thicknesses of rubber packing, but it failed under moderate pressures, though not sufficiently to seriously injure the plates except in

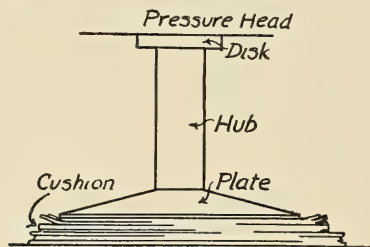


FIG. 7

the case of the cast iron. (Fig. 7). A cushion of dry sand forming a layer 2 inches thick was enclosed within a steel hoop a little larger than the plate, but the sand packed irregularly and failed to transmit a uniform pressure. A satisfactory cushion was finally composed of 11 layers of oak pieces, cut $24 \times 3 \times \frac{7}{8}$ in. piled in crosswise layers, leaving $\frac{1}{4}$ in. spaces between the pieces to permit expansion. (Fig. 8). This cushion proved to be sufficiently elastic and also able to sustain pressures sufficient to break the cast-iron plates. Indeed it later supported without great injury a load of 620 000 lb., or 31 times the safe pressure for which the plates were designed. Any injured pieces could easily be replaced in order to maintain the efficiency of the cushion.

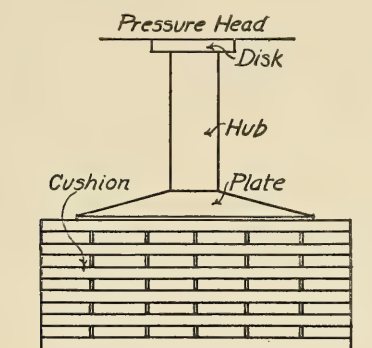


FIG. 8

Pressure was applied to the flat top of the plate by a hollow cylindrical cast-iron hub 12 inches long, 4 inches external diameter, and $\frac{3}{4}$ inch thickness of metal. Since the plates were not planed on top (which is seldom done in practical construction), several thicknesses of heavy manila paper were inserted between the hub and the plate. On the hub rested the pressure head of the testing machine, while the elastic cushion was placed between the plate and the bed of the machine. Thus the conditions of the test fairly represented those existing in actual structures, where the masonry yields somewhat and is not absolutely rigid like the bed of the testing machine.

The square steel plates were $\frac{15}{16}$ in. thick; the octagonal and circular steel plates were $\frac{3}{4}$ in. thick. The upward deflections of their outer edges were measured at 4 points to $\frac{1}{1000}$ in., and each plate was gradually loaded to 120 000 lb., or with six times its maximum safe load. This produced an average maximum deflection of 0.29 in., leaving a permanent set averaging 0.18 in., when the pressure was removed. The plate was thus dished, but no failure or cracks were produced.

These results show that a steel base plate bends more than one of cast iron, and that it does not so uniformly distribute its load over the masonry beneath it as a more inflexible cast-iron plate. It follows that the latter plate is preferable for the purpose. Empirical rules usually make steel plates one-half the thickness of cast-iron plates supporting equal loads.

Mr. Dick deduced from his experiments the following conclusions for steel plates.

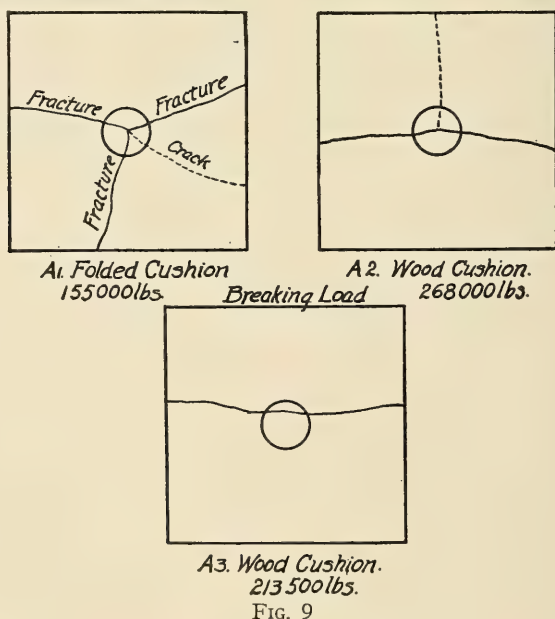
"1. The (preceding) formulas for the design of steel base plates are entirely safe.

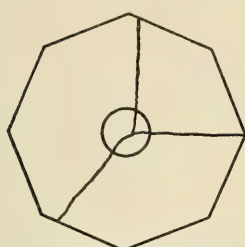
2. The limit of 16 000 pounds fiber stress permitted by the Chicago ordinance is perhaps too large, since marked deflections take place rapidly after this fiber stress has been exceeded.

3. Steel plates projecting more than two diameters of the hub (or column) beyond it, should be designed for deflection, or it would be better to use a cast-iron plate for large loads.

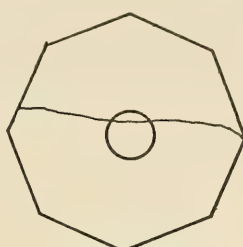
4. The circular is the most economical shape for a bearing plate."

The cast-iron plates were beveled on top from the hub to a uniform thickness of $\frac{3}{8}$ in. at the edges, the bottom being a plane surface. They were cast and tested in sets of threes of each form. The square plates (Fig. 9) were $2\frac{7}{16}$ inches thick beneath the hub; the octagonal plates (Fig. 10) were $2\frac{1}{8}$ inches, while the circular plates (Fig. 11) were $2\frac{7}{16}$ inches. All cast-iron plates were tested to fracture, which occurred with the load indicated in the figures for each plate. Plates A 1, B 1 and C 1 were tested on the cushion of folded blankets, etc. (Fig. 7), which crushed and distributed the pressure unequally, the plate thus failing under a smaller load. The other plates were tested on the wooden cushion, Fig. 8.

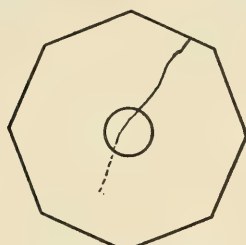




*C1. Folded Cushion
67000 lbs.*

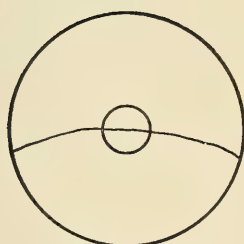


*C2. Wood Cushion
121000 lbs.*

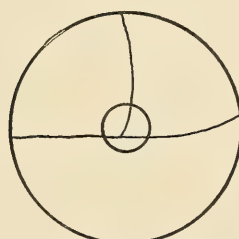


*C3. Wood Cushion.
117500 lbs.*

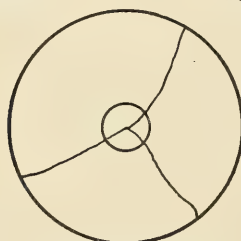
FIG. 10



*B1. Folded Cushion
139000 lbs.*



*B2. Wood Cushion
275000 lbs.*



*B3. Wood Cushion
275000 lbs.*

FIG. 11

From the results of these tests, Mr. Dick deduced the following conclusions for cast-iron plates.

"1. The (preceding) formulas for the design of cast-iron plates may be used with safety.

2. A greater fiber stress than that permitted by the Chicago ordinance could be used with safety.

3. Cast iron is better adapted for base plates than steel, as it gives a uniform distribution of the load over the bearing area for a greater range of loading.

4. Cast iron will not deteriorate as rapidly as steel when in a damp place, and for this reason cast iron should be preferred."

Mr. Dick likewise notes that the fracture lines pass through the center of each plate and are not tangent to the hub, as assumed by the preceding formulas. He also suggests that assuming the fracture line through the center of each plate, the resultant moment of the pressures about this line may be found and equated to the resistance moment of the fracture section. But since this procedure would render the formulas much more complex and increase the labor of designing a plate, the extra labor would not be repaid, being unnecessary for safety.

The direction of the fracture line in the plates tested was sometimes changed by the influence of side cracks, probably due to slight irregularities in the distribution of the pressure, or perhaps to slight flaws in the castings.

VI. NEW FORMULAS

The new formulas proposed are based on the following principles, the result of a theoretical investigation and of the nature of the failures of the plates.

1. The line of fracture is a shorter diameter of the plate.

2. The breaking moment about this line is greater than that about a line tangent to the column or hub.

3. The weight of a base plate is very small in proportion to the load transmitted by it, and it may safely be neglected in the formulas.

4. The pressures at the top and the bottom of the plate are then equal and act in opposed directions with unequal lever arms.

5. Their moments about the fracture line being necessarily unequal, their resultant maximum safe moment is equal to the maximum safe resisting moment of the fracture section of the plate.

VII. RESULTANT BENDING MOMENT ACTING ABOUT FRACTURE LINE

Let A = total area of the plate in square inches;

P = total load in pounds transmitted by it;

L' = perpendicular distance in inches from fracture line to center of upward pressures on one-half the area of the plate;

then $L' = 0.25 \times$ length in inches of a wall or bearing plate;

$= 0.25 \times$ side of a square plate;

$= 0.2187 \times$ inscribed diameter of octagonal plate;

$= 0.2122 \times$ diameter of circular plate.

Let L'' = perpendicular distance in inches from fracture line to center of downward pressures on one-half the area of the plate;

then $L'' = 0.25 \times$ width of a beam or girder on a bearing plate;

$= 0.25 \times$ side of a solid square post or column;

$= 0.2187 \times$ diameter of solid octagonal post or column;

$= 0.2122 \times$ diameter of solid cylindrical post or column.

Let R = radius of outer circle inscribed in cross section of hollow square or cylindrical column;

r = radius of inner circle inscribed in hollow square or round column;

Then $L'' = 0.500 \frac{R^3 - r^3}{R^2 - r^2}$, for a hollow square column.

Limiting values are $\begin{cases} 0.500R & \text{for a solid column.} \\ 0.750R & \text{for a very thin shell column.} \end{cases}$

Also $L'' = .424 \frac{R^3 - r^3}{R^2 - r^2}$, for a hollow cylindrical column.

Limiting values are $\begin{cases} .424R & \text{for a solid column.} \\ .637R & \text{for a very thin shell column.} \end{cases}$

These values of L'' may readily be found by calculation, but much more easily by the aid of the graphical table, Fig. 12.

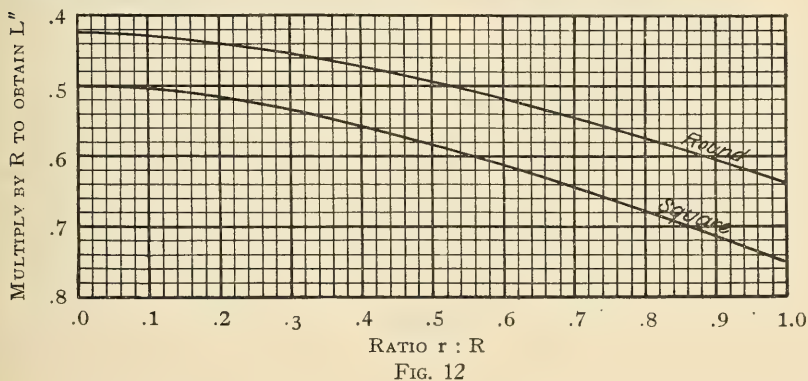


FIG. 12

Example. Assume a hollow cylindrical column, 12 in. external and 9 in. internal diameter.

Then
$$\frac{r}{R} = \frac{4.5}{6.00} = 0.75.$$

By the table, Fig. 12, $L'' = 0.56 R = 3.36$ in.

VIII. RESISTANCE MOMENT OF FRACTURE SECTION

The fracture section is a plane vertical section through the fracture line.

Let f = maximum safe fiber stress in pounds per square inch.

B = length in inches of fracture section.

t = thickness in inches of plate at center under column.

I = moment of inertia of the fracture section.

c = vertical distance in inches from horizontal neutral axis to bottom of fracture section.

Then $\frac{fI}{c}$ = maximum safe resistance moment of fracture section in general.

(a) For a rectangular fracture section of plate of uniform thickness,

$$\frac{fBt}{6} = \text{maximum safe resistance moment.}$$

(b) For tapered section with sharp edges. (Fig. 13.)

Let k = length in inches of horizontal top of section under column or diameter of column.

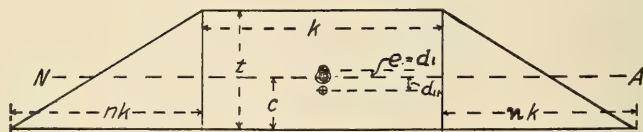


FIG. 13

nk = length in inches of each tapered portion of the fracture section.

$B = k(2n + 1)$ = length in inches of fracture section.

$A' = kt$ = area in square inches of rectangle in Fig. 13.

$A'' = nkt$ = area in square inches of both triangles in Fig. 13.

$d' = \frac{nt}{6(n+1)}$ = vertical distance in inches from center of gravity of rectangle to neutral axis of fracture section, Fig. 13.

$d'' = \frac{t}{6} - \frac{nt}{6(n+1)}$ = vertical distance from center of combined triangles to neutral axis of fracture section, Fig. 13.

$c = d'' + \frac{t}{3}$ = vertical distance in inches from neutral axis to bottom of fracture section.

Also $I = \frac{kt^3}{12} + ktd'^2$ = moment of inertia for rectangle.

$I = \frac{nkt^3}{18} + nkt d''^2$ = moment of inertia for combined triangles.

Finally $\frac{fI}{c} = \frac{fk}{c} \left[\frac{t^3}{12} + td'^2 + \frac{nt^3}{18} + nt d''^2 \right]$ = safe moment of resistance of fracture section of the plate. (7)

(c) For tapered section with thick edges (Fig. 14)

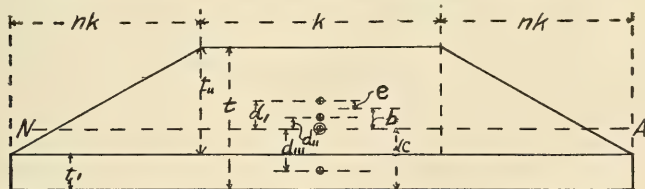


FIG. 14

Divide the fracture section into two rectangles and two triangles as in the figure.

Let t = thickness in inches at the middle of the plate.

t' = thickness in inches at the edges.

$t'' = t - t'$ = thickness of the taper in plate.

Then $A' = kt''$ = area in square inches of the upper rectangle.

$A'' = nkt''$ = area in square inches of combined triangles.

$A''' = (2n + 1) kt' =$ area in square inches of lower rectangle.

$e = \frac{nt''}{6(n + 1)} =$ vertical distance in inches from center of gravity of upper rectangle to joint center of gravity of this rectangle and combined triangles.

$$b = \left(\frac{t}{2} - e \right) \frac{A'''}{A' + A'' + A'''} \\ = \left(\frac{t}{2} - e \right) \left[\frac{(2n + 1)t'}{t'' + nt'' + (2n + 1)t'} \right] = \text{vertical distance in inches from the preceding joint center of gravity to the neutral axis of fracture section.}$$

Then $d' = e + b =$ vertical distance in inches from center of gravity of upper rectangle to neutral axis of fracture section.

$d'' = d' + \frac{t''}{6} =$ vertical distance from center of gravity of combined upper rectangle and both triangles to neutral axis of fracture section.

$$d'' = \frac{t}{2} - d' = \text{vertical distance in inches from center of gravity of lower rectangle to neutral axis of section.}$$

Then $I' = \frac{kt''^3}{12} + kt''d'^2 =$ moment of inertia of upper rectangle about the neutral axis.

$I'' = \frac{nkt''^3}{18} + nkt''d''^2 =$ moment of inertia of combined triangles about the neutral axis.

$I''' = \frac{(2n + 1)}{12} kt'^3 + (2n + 1) kt'd''^2 =$ moment of inertia of lower rectangle about the neutral axis.

Finally, summing these results for moment of inertia of entire section:

$$\frac{fI}{c} = \frac{fk}{c} \left[\frac{t''^3}{12} + td'^2 + \frac{nt''^3}{18} + nt''d''^2 + \frac{(2n + 1)t'^3}{12} + (2n + 1)t'd''^2 \right] =$$

resistance moment of fracture section of a plate with thick edges $= t'$. (8)

IX. METHOD OF APPROXIMATION

As cast-iron plates are generally made with thick edges, the practical application of the last formula is quite tedious. In order to apply it, it becomes necessary first to assume the thicknesses t , t' and t'' , then using the preceding formulas to determine the corresponding safe resistance moment of the fracture section. This process must doubtless be repeated several times before a plate is found which has the required safe moment of resistance of section. Hence the necessity for a simplification of the method by directly obtaining the required values of the thicknesses t , t' and t'' , which is accomplished in the following manner.

By the formula for a rectangular fracture section, the values of

$$\frac{I}{c} = \frac{bt^2}{6} = \frac{kt^2}{6} (2n + 1) \quad (9)$$

are computed for $n = 0$, $n = 1$, $n = 2$, $n = 3$, $n = 4$, $n = 5$, and these values lie in a straight line, when they are plotted as in the uppermost line in Fig. 15.

By formula (7) for tapered plates with sharp edges, are next computed the values of $\frac{I}{c}$ corresponding to $n = 0$, $n = 1$, $n = 2$, $n = 3$, $n = 4$, and $n = 5$. These values are then plotted in Fig. 15, forming the slightly curved and dotted line, next to the lower straight line. Joining the ends of the curve by the straight full line, this is found to almost coincide with the curved line, for which it may be substituted with a slight error on the safe side.

Similarly for $n = 5$ only, $\frac{I}{c}$ is computed for edge thickness $t' = 0.1t$, $0.2t$, $0.3t$, $0.4t$, $0.5t$, $0.6t$, $0.7t$, $0.8t$, and $0.9t$. These values are laid off on the vertical for $n = 5$, and straight radial lines are drawn to these points in Fig. 15. The corresponding per cents of resistance may then be easily computed for $n = 5$, as written in Fig. 15, and which signify that the resistance moment of a tapered fracture section is a certain per cent of that of a rectangular section of equal thickness, only for $n = 5$.

It now remains to determine this per cent for any other value of n .

The graphical table in Fig. 16 is readily computed and plotted from the data obtained in Fig. 15. It is used as follows:

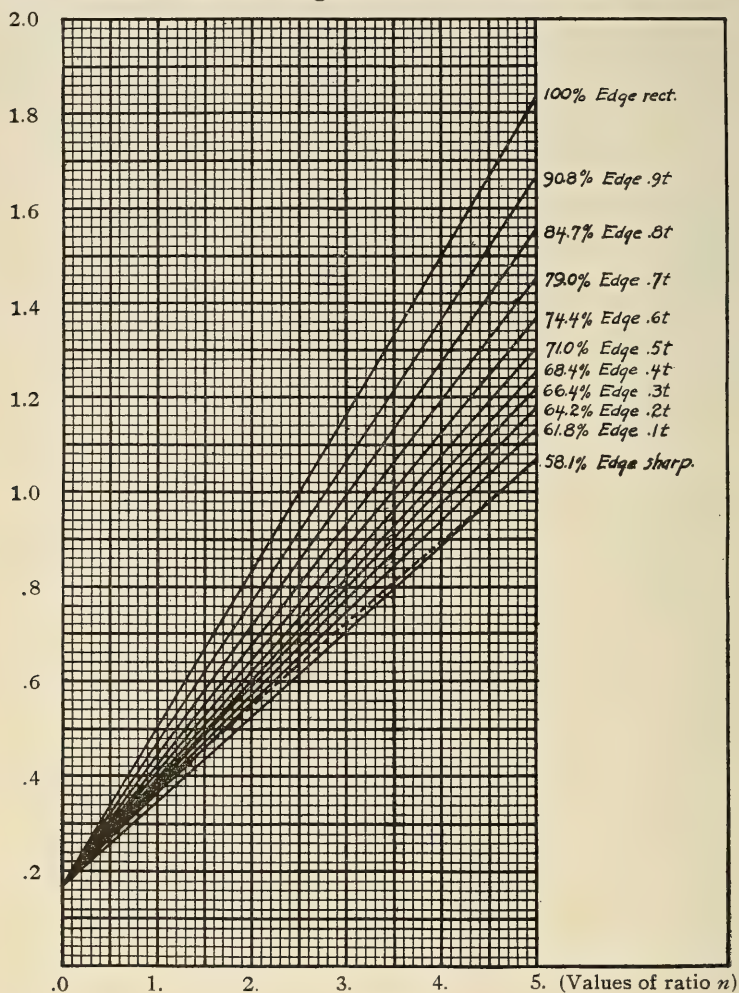


FIG. 15

Let @ = per cent of resistance moment of a rectangular fracture section, which is possessed by a tapered section with the same thickness t and the same value of n .

Example 1. Let $t' = 0.3 t$ = edge thickness and $n = 2$.

A vertical through 2 in Fig. 16 intersects the curve 0.3 on a horizontal through 70.5 at the left, which is the required per cent.

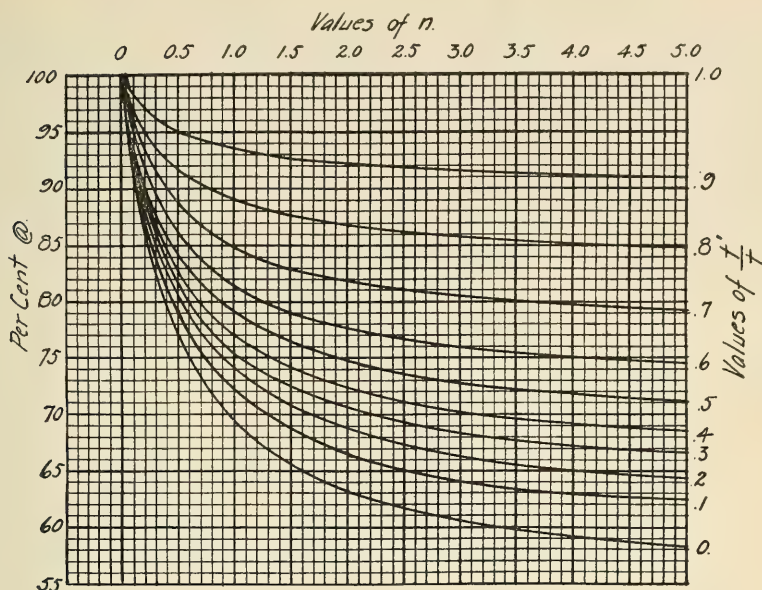


FIG. 16

Example 2. Let $t' = 2.5$ and $n = 3.5$.

A vertical through 3.5 intersects the interpolated curve 2.5 on a horizontal through 70.2 at the left, the required per cent.

It is further evident that the actual thickness t of a tapered plate must be somewhat greater than that of a plate of uniform thickness, when both are required to possess equal resistance moments.

The general formula for base plates is:

$$t = \sqrt{\frac{3P}{fB} (L' - L'')} =$$

thickness in inches for a plate of uniform thickness. (10)

Or
$$t = \frac{1}{50} \sqrt{\frac{3P}{B} (L' - L'')} =$$

thickness for a cast-iron plate. (11)

Let $@$ = per cent corresponding to $\frac{t'}{t}$ and n , found by table (Fig. 16)

Then for cast iron,
$$t = \sqrt{\frac{100}{@}} \frac{1}{50} \sqrt{\frac{3P}{B} (L' - L'')} = \text{required}$$

 thickness t under the column for a tapered cast-iron plate, possessing a resistance moment equal to that of a plate of uniform thickness t determined by formula 11. (12)

X. COMPLETE FORMULAS FOR PLATES OF UNIFORM THICKNESS

By equating the resultant bending and safe resistant moments acting about the neutral axis of the fracture section of the plate, the following general formulas are obtained:

The primary formula is:

$$M = \frac{P}{2} (L' - L'') = R = \frac{fI}{c}. \quad (13)$$

(a) Bearing plate on wall (Fig. 17)

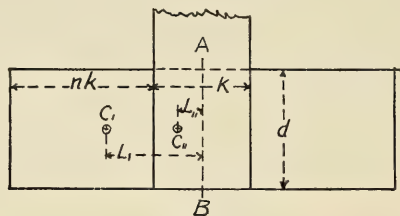


FIG. 17

Let d = width in inches of the plate, usually equal to the thickness of the wall.

Then

$$\frac{P}{2} (L' - L'') = \frac{f d t^2}{6}.$$

Or

$$\frac{P n k}{4} = \frac{f d t^2}{6}.$$

Hence $t = \sqrt{\frac{3 P n k}{2 f d}} = \text{thickness of the plate in inches.} \quad (14)$

And $t = \frac{1}{103.3} \sqrt{\frac{P n k}{d}} = \text{thickness in inches of a steel plate.} \quad (15)$

$t = \frac{1}{44.7} \sqrt{\frac{P n k}{d}} = \text{thickness of cast-iron plate, } f = 3000 \text{ lb.} \quad (16)$

$t = \frac{1}{40.8} \sqrt{\frac{P n k}{d}} = \text{thickness of cast-iron plate, } f = 2500 \text{ lb.} \quad (17)$

If a square or cylindrical column stands on the bearing plate instead of the end of a beam resting thereon, L'' is to be found and then inserted in the general formula, by which t may then be found. (Sec. VII). The general formulas then become:

$$t = \frac{1}{103.3} \sqrt{\frac{P}{d} \left(\frac{nk}{2} + \frac{k}{4} - L'' \right)} = \text{thickness for steel plate.} \quad (18)$$

$$t = \frac{1}{44.7} \sqrt{\frac{P}{d} \left(\frac{nk}{2} + \frac{k}{4} - L'' \right)} = \text{thickness for cast-iron, } f = 3000 \text{ lb.} \quad (19)$$

$$t = \frac{1}{40.8} \sqrt{\frac{P}{d} \left(\frac{nk}{2} + \frac{k}{4} - L'' \right)} = \text{thickness for cast-iron, } f = 2500 \text{ lb.} \quad (20)$$

Formulas 16, 17, 19 and 20 are also applicable to cast-iron bearing plates tapered in thickness from beam or column to each end, since the fracture section always remains rectangular in form.

(b) Square plate (Fig. 18)

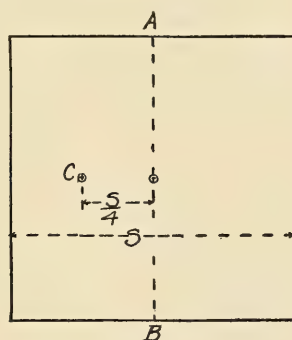


FIG. 18

Let S = side of square plate in inches.

$$\text{Then } t = \sqrt{\frac{3}{fS} \left(\frac{S}{4} - L'' \right)} = \text{thickness of plate in inches.} \quad (21)$$

$$t = \frac{1}{73} \sqrt{\frac{P}{S} \left(\frac{S}{4} - L'' \right)} =$$

thickness of steel plate in inches.

(22)

$$t = \frac{1}{31.6} \sqrt{\frac{P}{S} \left(\frac{S}{4} - L'' \right)} =$$

thickness for cast-iron, $f = 3000$ lb.

(23)

$$t = \frac{1}{28.9} \sqrt{\frac{P}{S} \left(\frac{S}{4} - L'' \right)} =$$

thickness for cast-iron, $f = 2500$ lb.

(24)

(c) Octagonal plate (Fig. 19)

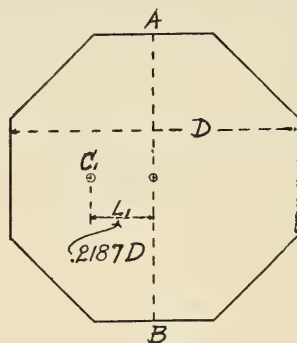


FIG. 19

Let D = inscribed diameter of octagon.

$$L' = .2187D.$$

$$t = \sqrt{\frac{3P}{fD} \left(.2187D - L'' \right)} =$$

thickness of plate in inches.

(25)

$$t = \frac{1}{73} \sqrt{\frac{P}{D} \left(.2187D - L'' \right)} =$$

thickness of steel plate.

(26)

$$t = \frac{1}{31.6} \sqrt{\frac{P}{D} \left(.2187D - L'' \right)} =$$

thickness of cast-iron plate, $f = 3000$ lb.

(27)

$$t = \frac{1}{28.9} \sqrt{\frac{P}{D} (.2187D - L'')} =$$

thickness of cast-iron plate, $f = 2500$ lb. (28)

(d) Circular plate (Fig. 20)

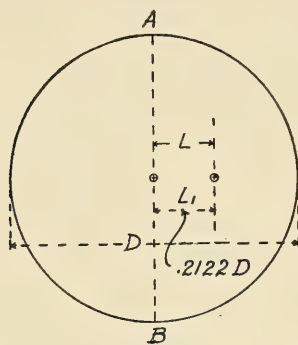


FIG. 20

Let D = diameter of the plate in inches.

$$L' = .2122D.$$

$$t = \sqrt{\frac{3P}{fD} (.2122D - L'')} =$$

thickness of the plate. (29)

$$t = \frac{1}{73} \sqrt{\frac{P}{D} (.2122D - L'')} =$$

thickness for steel plate. (30)

$$t = \frac{1}{31.6} \sqrt{\frac{P}{D} (.2122D - L'')} =$$

thickness for cast-iron, $f = 3000$ lb. (31)

$$= \frac{1}{28.9} \sqrt{\frac{P}{D} (.2122D - L'')} =$$

thickness for cast-iron, $f = 2500$ lb. (32)

XI. FOR PLATES OF TAPERED THICKNESS

These comprise all cast-iron base plates, which are always made thinner at their edges for the sake of economy. Bearing plates of cast iron set on walls, however, have a rectangular fracture section, for which direct formulas have already been given. (Formulas 16, 17, 19, 20.)

The thickness required at the middle of a tapered cast-iron plate may now be easily found.

1. Compute the thickness for a rectangular fracture section.
2. Assume the desired ratio $\frac{t'}{t}$ of thickness at edge and middle.

3. By the table, Fig. 16, determine the per cent @ of its resistance in comparison with a plate of rectangular section of equal width and thickness.

4. By formula 12 compute the required actual thickness t at the middle of the plate. Then t' is easily found.

Example. A hollow cylindrical cast-iron column has an external diameter of 6 in., is $\frac{3}{4}$ -in. thick and transmits a load of 60 000 lb. to the plate. Required the safe dimensions of a square cast-iron base-plate; fiber stress 2500 lb. per sq. in.; ratio $\frac{t'}{t} = 0.15$; safe resistance of masonry under plate = 125 lb. per sq. in.

$$\sqrt{\frac{60\,000}{125}} = 21.91 \text{ in.} = \text{side of plate required.}$$

$$nk = \frac{21.91 - 6.}{2} = 7.96 ; n = \frac{7.96}{6.00} = 1.33.$$

For this column, $R = 3.00$, $r = 2.25$; $\frac{r}{R} = 0.75$.

By the table, Fig. 12, $L'' = 0.56$, $R = 1.68$ in.

By formula 24,

$$t = \frac{1}{28.9} \sqrt{60\,000 \left(\frac{21.91}{21.91} - 1.68 \right)} = 3.53 \text{ in.}$$

By the table, Fig. 16, for $\frac{t'}{t} = 0.15$ and $n = 1.33$, @ = 71 per cent.

By formula 12,

$$t = \sqrt{\frac{100}{71}} \times 3.53 = 4.19 \text{ in.} = \text{the required middle thickness,}$$

And $4.19 \times 0.15 = 0.63 \text{ in.} = \text{thickness at the edge of the plate.}$

XII. GRAPHICAL TABLES

It is evident from the example just worked out, that the calculations required for any particular base plate are quite simple and rapid, particularly if 4-place logarithms are employed. It is, however, entirely possible to devise a series of graphical tables for materially reducing this labor, thus saving valuable time and lessening liability to errors.

XIII. TABLE FOR DIMENSIONS OF BASE PLATES

Fig. 21 is a graphical table for determining by inspection the side of a square, or the diameter of an octagonal or round plate, required to safely transmit loads not exceeding 200 tons (400 000 lb.), allowing safe pressures of the plate on masonry between 50 and 250 lb. per sq. in. Fig. 22 is merely an enlarged portion of the same table for loads not exceeding 20 tons.

By the use of the upper scale corresponding to the shape of the plate, it is possible to employ this single table for square, octagonal and circular plates, by reading the required side or diameter on the proper scale.

Example. A plate is required to safely transmit a load of 100 tons, allowing a safe pressure of 125 lb. per sq. in. on the masonry beneath it.

Locating the intersection of a horizontal through 100 tons with the curve for 125 lb., and following a vertical through this point to the respective scales at the top of the table, we read the following values:

40.0 in. = side of a square plate required.

42.0 in. = diameter of an octagonal plate.

45.0 in. = diameter of a circular plate.

Pressures intermediate between the given curves can be easily located with sufficient accuracy.

XIV. TABLE FOR THE FACTOR $\sqrt{\frac{3P}{B}}$

The general formula for a plate of uniform thickness is

$$t = \sqrt{\frac{3P}{fB}} \quad (L' - L'') = \text{thickness in inches.} \quad (10)$$

This may be factored in the form

$$t = \sqrt{\frac{3P}{B}} \times \sqrt{\frac{L' - L''}{f}} = \text{thickness in inches.}$$

Fig. 23 exhibits the relations of the three quantities

P = total load in tons transmitted by the plate.

B = length in inches of the fracture section.

$$\sqrt{\frac{3P}{B}} = \text{one factor in the last formula.}$$

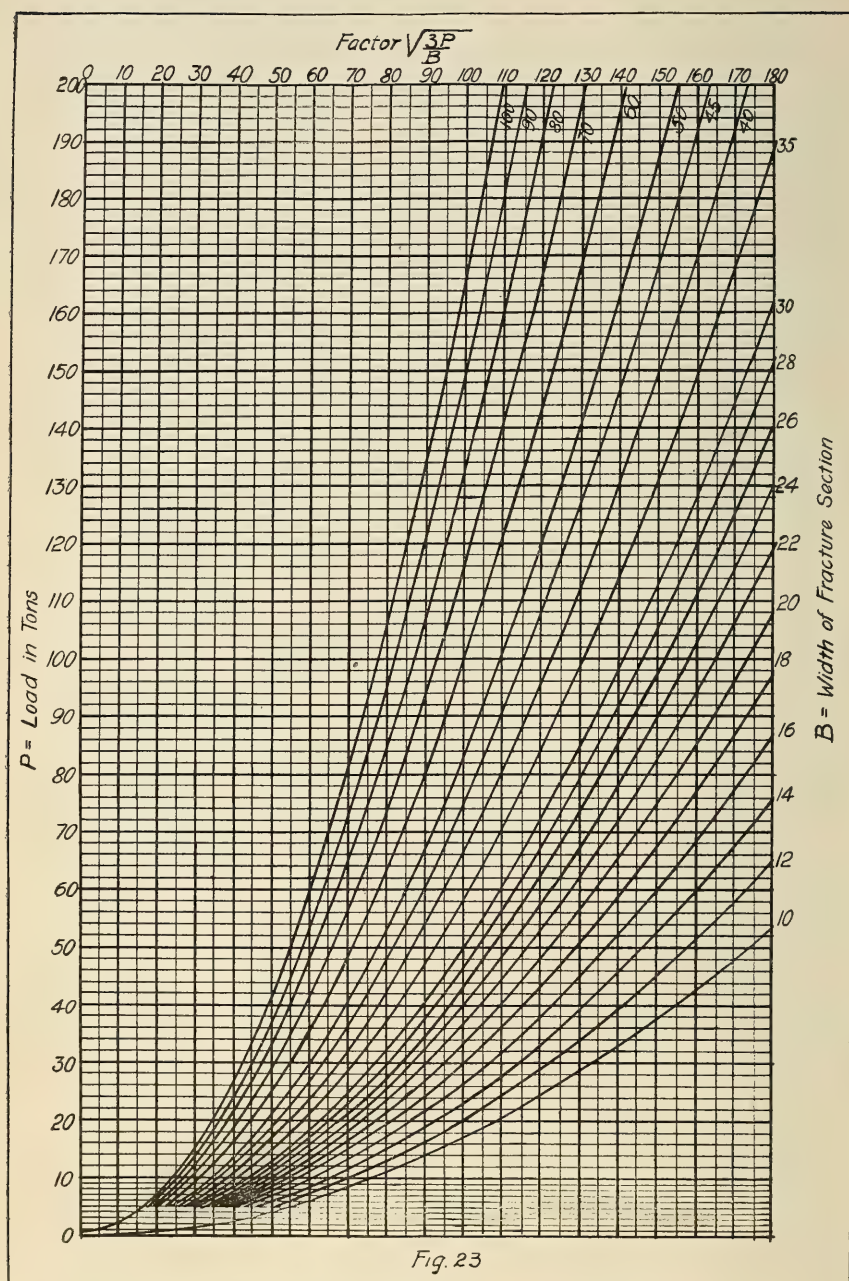
Example. Take the square plate in the last example. $P = 100$ tons, $B = 40.0$ in. The intersection of a horizontal through 100 tons with the curve for 40.0 in., and a vertical through this point gives at the top of the table $\sqrt{\frac{3P}{B}} = 122.5$.

Assume that a 12-in. cylindrical cast-iron column with $1\frac{1}{4}$ -in. metal stands on this base plate.

Then $\frac{r}{R} = \frac{4.75}{6.00} = 0.79$, and by the table in Fig. 12:

$$L'' = .572 \times 6.00 = 3.43 \text{ in.}; L' = \frac{40}{4} = 10.0 \text{ in.}$$

Hence $L' - L'' = 10.0 - 3.43 = 6.57$ in.



XV. TABLES FOR PLATES OF UNIFORM THICKNESS

The table in Fig. 24 exhibits the relations of the three quantities:

$\sqrt{\frac{3P}{B}}$ = the factor whose value has just been found from Fig. 23.

$L' - L''$ = difference in lever arms of the upward and downward bending moments.

t = thickness in inches represented by curved lines in the table.

In designing the tables in Fig. 24 and 25, the factor $\sqrt{\frac{L' - L''}{f}}$ is actually employed, but the device of separate vertical scales for the different values of f makes the table more convenient for use.

Resuming the last example and employing the table Fig. 24, a vertical through 122.5 at the top intersects a horizontal through 6.57 at the left, giving by estimation between the nearest curves the following values for t .

$$t = 2\frac{1}{2} \text{ in. for a steel plate.}$$

$$t = 2\frac{13}{16} \text{ in. for a wrought-iron plate.}$$

Employing the table, Fig. 25, in the same manner for cast-iron plate of uniform thickness:

$$t = 5\frac{3}{4} \text{ in. for fiber stress of 3000 lb. per sq. in.}$$

$$t = 6\frac{5}{16} \text{ in. for fiber stress of 2500 lb. per sq. in.}$$

Assuming 0.20 for the ratio $\frac{t'}{t}$, and $n = 1.17$, by the table, Fig. 16, @ = 72.5 per cent.

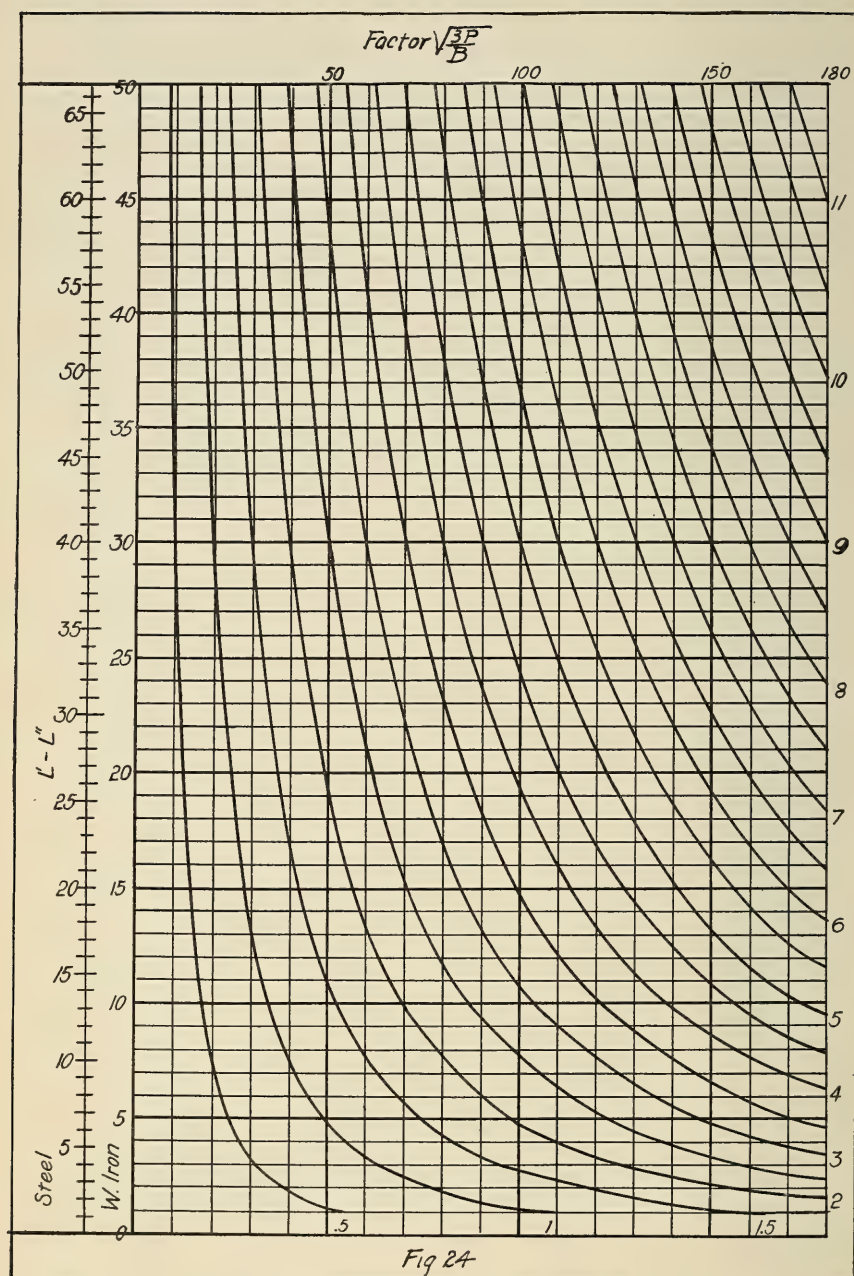
By formula 12,

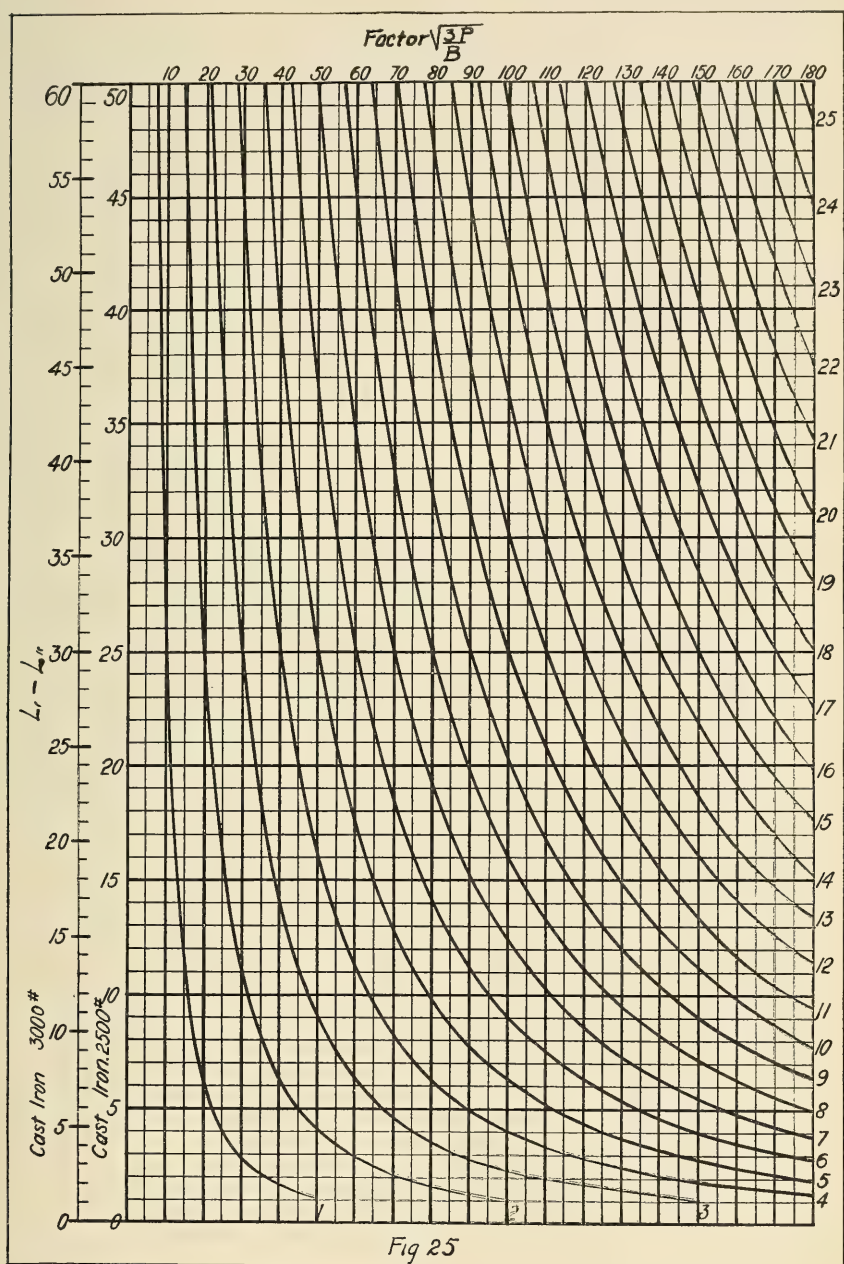
$$t = \sqrt{\frac{100}{72.5}} \times 5.75 = 6.76 \text{ in. at middle for } f = 3000 \text{ lb. per sq. in.}$$

$$t = \sqrt{\frac{100}{72.5}} \times 6.31 = 7.41 \text{ in. at middle for } f = 2500 \text{ lb. per sq. in.}$$

Then $6.76 \times 0.2 = 1.35$ in., and $7.41 \times 0.2 = 1.48$ in., the respective thicknesses at the edges required.

It will be seen that Fig. 24 contains two vertical scales, one for steel with fiber stress of 16 000 lb. per sq. in. and the other for wrought iron with fiber stress of 12 000 lb. per sq. in. Fig. 25 likewise has two vertical scales corresponding to fiber stresses of 3000 lb. and 2500 lb. per sq. in.





XVI. ADDITIONAL EXAMPLES OF THE USE OF THE TABLES

1. A bearing plate is 12 in. wide and rests on a 13-in. wall; it supports a load of 15 tons (30 000 lb.) transmitted by the end of a girder 12 in. wide. Safe pressure of plate on masonry = 100 lb. per sq. in. Safe fiber stress for cast iron = 2500 lb. per sq. in. Required its thickness.

$$\frac{15 \times 2000}{100 \times 12} = 25.0 \text{ in.} = \text{length of the plate,}$$

$$nk = \frac{25 - 12}{2} = 6.5 \text{ in.} = \text{projection of end beyond side of girder;}$$

By formula 17,

$$t = \frac{1}{40.8} \sqrt{\frac{Pnk}{d}} = \frac{1}{40.8} \sqrt{\frac{30\,000 \times 6.5}{12.0}} =$$

3.12 in., the thickness beneath the girder. The plate may be tapered from the girder to any desired thickness at its ends without danger, since its fracture section is always rectangular.

If the safe fiber stress be taken = 3000 lb. per sq. in.;

$$t = \frac{40.8 \times 3.12}{44.7} = 2.85 \text{ in., say, } 2\frac{7}{8} \text{ in.}$$

Or by the table, Fig. 21, a plate 17.25 in. square would be required.

$$\text{Hence, length } \frac{(17.25)^2}{12} = 25.0 \text{ in., as before.}$$

Also by the table, Fig. 23, the factor $\sqrt{\frac{3P}{B}} = 86.0$.

$$L' = \frac{25.0}{4} = 6.25; L'' = \frac{12.0}{4} = 3.00;$$

$$L' - L'' = 6.25 - 3.00 = 3.25 \text{ in.}$$

By the table, Fig. 25, $t = 3\frac{1}{8}$ in. as before.

Therefore, the graphical tables may also be used for bearing and wall plates.

2. A square base plate transmits a load of 50 tons to masonry with a safe resistance of 150 lb. per sq. in. Safe fiber stress 3000 lb. per sq. in. A column 7 in. external diameter and 1 in. thickness of metal stands on this plate.

By the table, Fig. 21, 22.7 in. = side of plate, and $n = 1.12$.

By the table, Fig. 23, $\sqrt{\frac{3P}{B}} = 114.5$.

$L' = 5.68$ in.; $L'' = 1.91$ in. by Fig. 12. $L' - L'' = 3.76$ in.

By the table, Fig. 25, $t = 3\frac{5}{16}$ in. = 3.31 in.

Assuming $\frac{t'}{t} = 0.25$, which is a commonly employed ratio, and $n = 1.12$, @ = 73.5 by the table in Fig. 16.

By formula 12,

$$t = \sqrt{\frac{100}{73.5}} \times 3.31 = 3.86 \text{ in.} = \text{thickness at middle, and}$$

$$t' = 3.86 \times 0.25 = 0.97 \text{ in. thickness at edges.}$$

3. A circular base plate transmits a load of 175 tons to masonry with a safe resistance of 175 lb. per sq. in. A column of metal 12 in. in diameter and $1\frac{1}{4}$ in. thick stands on this plate.

By the table, Fig. 21, 50.5 in. = diameter of the plate; $n = 1.60$.

By the table, Fig. 23, $\sqrt{\frac{3P}{B}} = 144$. Also $L' - L'' = 7.29$ in.

By the table, Fig. 24, $t = 3.10$ in. for a steel plate.

$t = 3.50$ in. for a wrought-iron plate.

By the table, Fig. 25, $t = 7.05$ in. for cast-iron plate, $f = 3000$ lb. per sq. in.

$t = 7.75$ in. for cast-iron plate, $f = 2500$ lb. per sq. in.

Assuming

$$\frac{t'}{t} = 0.25, \text{ and as } n = 1.60, \text{ by the table, Fig. 16, @} = 71.0.$$

Then

$$t = 7.05 \times \sqrt{\frac{100}{71}} = 8.37 \text{ in.} = \text{thickness beneath column, } f = 3000 \text{ lb.}$$

$$t = 7.75 \times \sqrt{\frac{100}{71}} = 9.20 \text{ in.} = \text{same, for } f = 2500 \text{ lb.}$$

Therefore

$$t' = 2.09 \text{ in. in the first case and } 2.30 \text{ in. in the second.}$$

4. Assume that in the last case the plate is to be square and that the safe resistance of the masonry is but 90 lb. per sq. in.

In the same manner as before, we easily find:

$$\text{Side of plate} = 62.2 \text{ in.; } n = 2.09.$$

$$\text{Factor } \sqrt{\frac{3P}{B}} = 130$$

$$t = 3\frac{5}{8} \text{ in. for a steel plate}$$

$$t = 4\frac{3}{4} \text{ in. for a wrought-iron plate}$$

$$t = 8\frac{3}{8} \text{ in. for cast-iron plate, } f = 3000 \text{ lb.}$$

$$t = 9\frac{1}{8} \text{ in. for same with } f = 2500 \text{ lb.}$$

$$\text{Assuming } \frac{t'}{t} = 0.25, \text{ and for } n = 2.09; @ = 69.5.$$

Then $t = 10.00$ in. thickness at middle in the first case and $= 10.95$ in the second. The corresponding values for t' are 2.50 and 2.74 inches.

5. A built steel column is composed of two 15-in. channels, one 15-in. I, and two $16 \times \frac{3}{4}$ -in. plates. It stands on a circular cast-iron base plate, which rests directly on a cylindrical sunken foundation pier of portland cement concrete, to which the plate transmits a load of 500 tons (1 000 000 lb.) Maximum safe fiber stress in cast iron is taken at 2500 lb. per sq. in. Safe resistance of the concrete pier is 175 lb.

per sq. in. Let $\frac{t'}{t} = 0.20$.

Required least safe diameter and thickness of the cast-iron plate.

$$\text{In this case, } \frac{1\,000\,000}{175} = 5714.3 \text{ sq. in., area of plate.}$$

$$d = \sqrt{\frac{5714}{.7854}} = 85.3 \text{ in.} = \text{diameter of the plate; } n = 2.17.$$

$$\text{By formula Sec. VII, } L' = 85.3 \times 0.2122 = 18.1 \text{ in.}$$

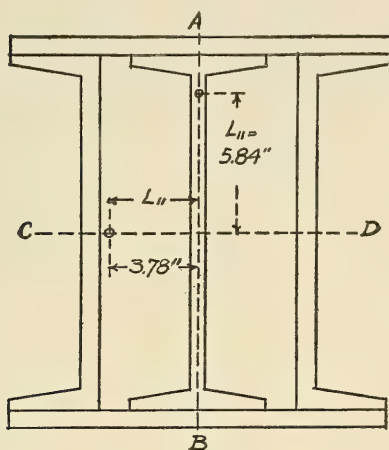


FIG. 26

For the given cross section of the steel column, Fig. 26, there may readily be found by the usual graphical methods:

$$L'' = 5.84 \text{ in. about the axis } CD.$$

$$L'' = 3.78 \text{ in. about the axis } AB.$$

Taking the smaller of these values and applying formula 32,

$$t = \frac{1}{28.9} \sqrt{\frac{P}{B} (L' - L'')} = \frac{1}{28.9} \times \sqrt{\frac{1\,000\,000}{85.3} (18.10 - 3.78)} = 14.18 \text{ in.}$$

Assuming $\frac{t'}{t} = 0.20$, and for $n = 2.17$, by table in Fig. 16,

$$@ = 68.0$$

Then $t = \sqrt{\frac{100}{68.0}} \times 14.18 = 17.20 \text{ in.} = \text{thickness under column,}$
 and $t' = 17.2 \times 0.20 = 3.44 \text{ in.} = \text{thickness at edge of plate.}$

Such a solid plate would be more simple and more easily set in place, and it might also be cheaper than the usual arrangement consisting of a cast-iron ribbed base plate or stool above a layer of short

steel 15-inch I-beams, which are set on the top of the concrete pier. This pier would also here require to be not less than 8 ft. 6 in. in diameter at the top.

These examples show that simple formulas and tables have been here devised, making the calculation of safe plain bearing and base plates a very simple matter.

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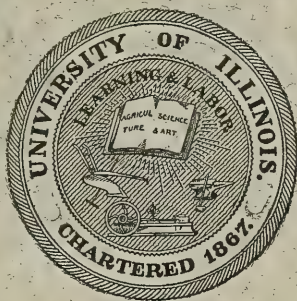
THE THERMAL CONDUCTIVITY OF FIRE-CLAY AT HIGH TEMPERATURES

BY

J. K. CLEMENT

AND

W. L. EGY



UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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THE THERMAL CONDUCTIVITY OF FIRE-CLAY AT HIGH
TEMPERATURES

By J. K. CLEMENT, PHYSICIST, U. S. G. S., TECHNOLOGIC BRANCH,
AND

W. L. EGY, RESEARCH FELLOW, DEPARTMENT OF PHYSICS,
ENGINEERING EXPERIMENT STATION

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TEMPERATURE MEASUREMENTS

I. INTRODUCTION ¹

The problem of thermal conductivity has for a long time furnished a favorite field of research for the physicist.² In reviewing the investigations of the past, many experiments, forming gradual approaches to a solution of this problem, will be found on record.³ Nearly all of these experiments, however, were made at temperatures between that of melting ice, and steam at atmospheric pressure, and in no instances were even moderately high temperatures reached.⁴ These experiments show that the chief difficulties have been the obtaining and maintaining of a high temperature, the determination of the quantity of heat conducted through the material, and the measurement of the correct temperature gradient in the specimen under test. Fortunately for present-day investigations, the electric heating coil and the thermocouple enable us to solve these problems with comparative ease and with a high degree of accuracy.

Although the investigation described in this bulletin was undertaken in the attempt to solve a specific problem,—the thermal conductivity of fire-clay at high temperatures,—the method developed will no doubt be of interest in other lines of work where the question of thermal conductivity is of importance. For instance, in all problems of refrigeration, this is a factor of the greatest importance. In the construction of cold storage buildings, a convenient method for test-

¹ The investigation described in this bulletin was conducted in the Physical Laboratory of the University of Illinois by W. L. Egy, a research fellow of the Engineering Experiment Station. Its inception is due to Dr. J. K. Clement, and to him also is due the credit for the selection of the general method. Dr. A. P. Carman, Professor of Physics, advised Mr. Egy concerning the later phases of the investigation.

² See "The Conductivity, Porosity and Gas Permeability of Refractory Materials," by S. Wolagidine and A. L. Queneau, in *Electro-Chemical and Metallurgical Industry*, Sept., 1909, p. 383; Oct., 1909, p. 433. It is a singular coincidence that after many years in which no work was done upon this subject, two attempts should be made independently and practically at the same time.

³ E. H. Hall, *Phys. Rev.*, Vol. X, p. 277. June, 1900. Holborn & Wlen, *Zeltsch. Ver. Deutsch. Ingen.*, Vol. 40, 1896. Lees & Chorlton, *Phil. Mag.*, Vol. 41, p. 495, Sec. 5, 1896. G. Glage, *Ann. d. Physik.*, Vol. 323, p. 904, Dec., 1905. C. Niven, *Roy. Soc. Proc.*, Vol. 76 A, p. 34, April 22, 1905. Tait, *Trans. Roy. Soc. Edin.*, Vol. 28, p. 717, 1879.

⁴ An account has recently been published of some very excellent work done by Dr. Wilhelm Nusselt on the "Thermal Conductivity of Heat Insulators." Some of his measurements were made at temperatures as high as 550° C. See *Engineering*, Vol. 87, pp. 1, 2, Jan. 1, 1909.

ing the various building materials would be of great value, although, of course, working at low temperatures would present a somewhat different problem.¹

The primary object of these investigations in determining the thermal conductivity of fire-clay was to obtain information concerning the loss of heat through the walls of boiler furnaces. It is a well-known fact that considerable heat escapes through the walls of furnaces, but no idea of the amount of this heat has heretofore been obtained by direct methods. Nor do we have any definite knowledge of the effect of this heat, which passes through the walls, upon the different materials of which they are composed. While the engineer knows that the thicker the wall, the less heat is lost, he does not know how far he will be justified in increasing the thickness of the wall, until he has secured accurate data of the quantity of heat lost in this way.

To illustrate,—knowing the thermal conductivity, K , of brick, the dimensions of the furnace, and the inside and outside temperatures of the walls, the quantity of heat transmitted through them may readily be calculated. Taking the specific case of a 210 H. P. Heine boiler at the University of Illinois, when working under full load,—the area of walls exposed to the hot gases is about 364 sq. ft., and the thickness of the same about 20 in. The average temperature of the inside of this area is approximately 1400° F., and of the outside, 150° F. If we now take the value of K as found for that test-piece which was nearest like the brick in the setting, that is, $K=.0026$, (See Curve No. 2), and calculate the heat conducted through the walls we have, using *c. g. s. units*,

$$Q = .0026 \frac{.555 (1400-150)}{2.54 (20)} 929 (364) \times 3600$$

(See formula 1, page 4.)

$$Q = 43,400,000 \text{ calories per hour} \\ \text{or } 172,000 \text{ B. t. u. per hour}$$

This is about 1.6 per cent of the total heat generated. These figures are only approximations, but they show that with careful measurements, the heat lost through the various parts of the walls may be calculated directly.

¹ The conductivity of the substances in the earth's crust is of interest to geologists. The British Association for the Advancement of Science had a committee working for seven years to determine the conductivity of some of the rocks in the British Isles. (Herschel, Lebour, and Dunn, Rep. Brit. Assn., Vol. 49, 1879.)

II. PRINCIPLES OF THERMAL CONDUCTIVITY

A brief resumé of the principles of thermal conductivity follows:

The quantity of heat, Q' , flowing through a given wall is proportional to the difference in temperature, $T_1 - T_2$, of the two faces. For a given difference in temperature, Q' is inversely proportional to the thickness, r . The heat flowing through a section of the wall will, of course, be proportional to the area, A , of that section. Q' is necessarily proportional also to the time, t , over which measurements are taken. Using these principles,

$$Q' = K \frac{T_1 - T_2}{r} At \dots \dots \dots (1)$$

K is a constant for the given substance at any temperature, and is called the internal thermal conductivity or simply the thermal conductivity of that material. If Q is expressed in calories; $T_1 - T_2$ in centigrade degrees; A , in square centimeters; r , in centimeters; and t , in seconds, K will be in *c. g. s.* units.

If we consider a lamina of infinitesimal thickness, dr , the difference in temperature between its faces being dT , for a time, dt ,

$$Q' = K \frac{T - (T + dT)}{dr} A dt = -KA \frac{dT}{dr} dt \dots \dots (2)$$

The expression $\frac{dT}{dr}$ is called the temperature gradient at the point in question, or in other words, the change in temperature per unit thickness.

$$\text{From equation (2)} \quad K = -\frac{Q}{A} \frac{dr}{dT} \dots \dots \dots (3)$$

where Q is the heat flowing across the area A in unit time.

From the above expression, it may be seen that in order to determine the thermal conductivity of a substance, it is necessary to measure the quantity of heat flowing through a unit area, and the temperature gradient. The most accurate method of measuring Q , is to generate a known quantity of heat by means of an electric heating circuit, in such a manner that all the heat generated must flow through

the substance to be tested. If a constant quantity of heat is generated until conditions have reached an equilibrium, then the quantity of heat conducted through the material per second must be equal to the quantity generated per second. This method may be used with a heating coil either in a hollow sphere or in a long cylinder. The latter form was chosen for these tests because of the experimental difficulties arising in the former.

In using this method, the assumption is made that there will be no escape of the heat longitudinally at the middle of the cylinder; that is, the exact amount of heat generated by a centimeter length of the coil, taken at the middle, must flow out through the corresponding circular section of just one centimeter thickness. To avoid errors from this cause, the length of the cylinder must be several times greater than its diameter.

The test-pieces were made into cylinders about 40 cm. in length and 12 cm. in diameter, with a hole through the center about 3.5 cm. in diameter for the reception of the heating coil. Four longitudinal holes about 3 mm. in diameter were made, in which thermocouples could be placed for the measurement of the temperature.

Applying equation 3 to the case of a cylinder, the heat, Q , generated by 1 cm. length of the coil in unit time is expressed by

$$Q = \frac{.2394}{l} \frac{EI}{1} \quad \text{calories}$$

where E represents volts, I , amperes, and l , the length of the coil in centimeters. The constant, .2394, is the reciprocal of the mechanical equivalent of a calorie expressed in joules or watts. The area perpendicular to the flow of heat at a distance r from the axis is $2\pi r$ per unit length. Substituting for Q and A in equation 3

$$K = - \frac{.2394}{2\pi l} \frac{EI}{1} \cdot \frac{dr}{dT} \dots\dots\dots (4)$$

Assuming that K is constant between the temperatures T_1 and T_2 and integrating

$$K = \frac{.2394}{2\pi l} \cdot \frac{EI}{T_1 - T_2} \log (r_2/r_1) \dots\dots\dots (5)$$

where T_1 and T_2 are the temperatures at points distant r_1 and r_2 , respectively, from the axis. For any given values of r_1 and r_2 , the only variables in this equation are EI , the electrical watts dissi-

pated in the coil, and $T_1 - T_2$, the difference in temperature between r_1 and r_2 . Thus our expression may be reduced to

$$K = C \frac{EI}{T_1 - T_2} \dots\dots\dots (6)$$

where

$$C = \frac{.2394 \log (r_2/r_1)}{2\pi l}$$

III. DESCRIPTION OF THE APPARATUS

Cylinders.—The cylinders tested were made by the Laclede-Christy Clay Products Company, St. Louis, Missouri. Twelve test-pieces were obtained, made up from four different mixtures, which were marked *A*, *B*, *1* and *3*.

Those marked *A* were of a dark reddish-brown color and contained no gravel. The structure appeared similar to sandstone. After heating in the test, these pieces were cracked in a great many places. The pieces marked *B* were also of a reddish-brown color, but were of medium coarse structure. They contained very small pieces of white gravel throughout the mass. Those marked *1* were a little coarser than the *B* cylinders and were brown in color. They contained a very small amount of gravel. Cylinders *3* were almost white and very coarse. They contained a large amount of gravel.

One cylinder of each composition was tested at temperatures ranging from 400° C. to 800° C. or 900° C. The remaining pieces were tested at only one temperature. One of the cylinders, marked *1*, could not be tested because the holes in it for the insertion of the thermocouples were not deep enough.

Furnace.—Fig. 2 shows a longitudinal section of the furnace ready for use. *aa* is the test-piece. This was surrounded by a larger cylinder, *bb*, of fire-clay, in order to get uniform radiation from *aa*, and also to maintain higher temperatures. Coverings, *cc*, were placed over each end to prevent loss of heat in this direction. The whole was supported by an open framework of strap iron. A thermocouple was placed in each of the holes, *D* and *F*.

Heating Coil.—The heating coil was made of pure nickel wire about 1.8 mm. in diameter, wound nine turns to the inch upon a ½-in. porcelain electric insulator tube. Commercial insulator tubes 20 in. long were taken for this purpose and the enlarged end cut off, leaving

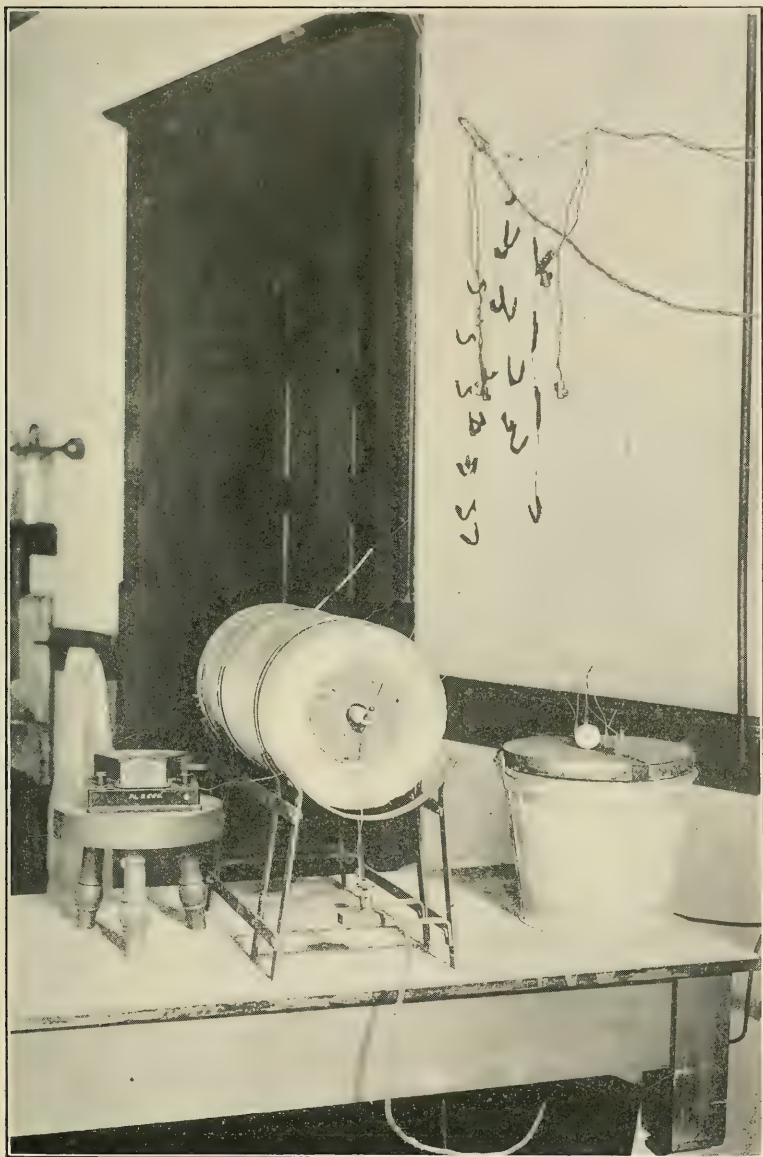


FIG. 1 TEST-PIECE SURROUNDED BY FIRE-CLAY JACKET—ALSO
SHOWING THERMOCOUPLES IN PLACE

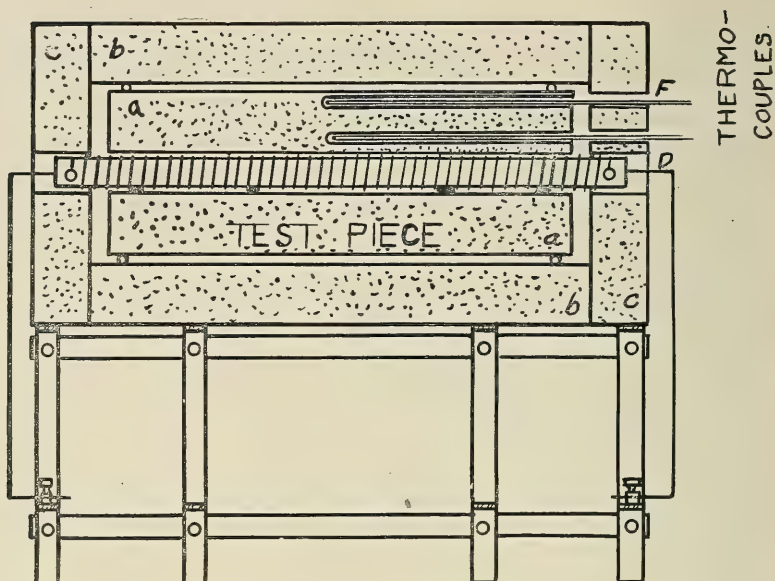


FIG. 2 SECTION OF FURNACE

them 18 or 19 in. long. Small holes were chipped in the ends of each tube, and the ends of the wire pulled tightly through these holes, thus holding the wire in place. The holes were $16\frac{1}{8}$ in. apart, allowing 145 turns of wire, or an equivalent length of 40.9 cm. Potential leads were fastened to the power wire where it emerged from the insulator, by winding one end of a piece of smaller wire tightly about it. The place where this connection was made had a rather high temperature, so nickel was used to prevent any thermo-electric effect at the junction.

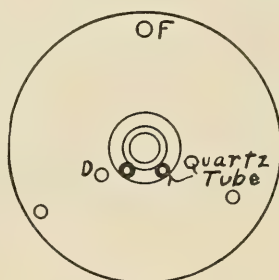


FIG. 3

The coil was at first supported in the cylinder by two small pieces of quartz tubing at each end (see Fig. 3). At the higher temperatures, however, the insulator softened and sagged down in the middle, and two additional pieces of quartz were placed under it, each one-third the distance from either end. The holes in the end of the furnace were packed with asbestos to prevent the escape of heat. The heating coil was made a few turns longer than the test-piece to prevent cooling of the ends.

IV. METHOD OF MEASUREMENTS

The current was measured by a Weston direct-reading portable standard millivoltmeter and shunt. The current was taken from 110-volt mains and was regulated by means of two large rheostats, as in the calibration work, (Appendix). As it was necessary to maintain the current constant to one-tenth of an ampere for several hours at a time, and the line voltage varied considerably, a storage battery was placed across the mains as shown in Fig. 4. By means of another resistance, the current from the mains was adjusted to a few amperes

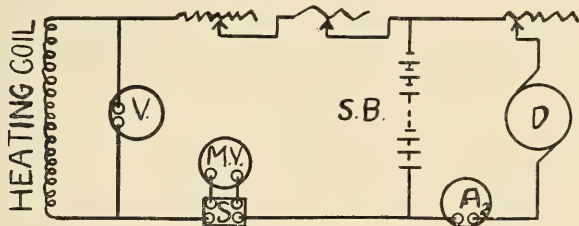


FIG. 4

less than that flowing through the furnace. In this way only a few amperes were drawn from the battery and its voltage remained constant through a considerable change of the line voltage. This was not always sufficient, however, for satisfactory operation.

The voltage drop through the coil was measured by a Weston portable voltmeter, the smallest division of which corresponded to one volt. The temperature coefficient of nickel is very large, and the resistance of the wire varied considerably with the temperature. As the turns at the end of the coil were somewhat cooler than those

in the middle, their resistance was less, and the average voltage drop per centimeter for the whole coil would be less than the drop per centimeter of the central portion. As the average value was used in the calculations, an error would thus be introduced. This was compensated for, by having the potential leads connected to the heating circuit, as stated above, outside the insulator, thus adding to the potential drop across the actual 145 turns, the drop in the wire from the last turn to the point of connection.

The temperatures were measured by platinum-platinum-rhodium thermocouples, made by Heraeus, in Germany, and calibrated by the melting-point method described in the Appendix. The couples were also calibrated in opposition as a differential couple. This was done by placing both couples in a quartz tube in a large piece of iron and heating the iron up to about 1100°C ., taking the reading of the differential couple at various temperatures. The couples were placed in the small holes (D, F, Fig. 2) in the test-piece far enough so that the junctions were midway between the ends. The two wires were insulated from each other by placing very small porcelain tubing over the platinum-rhodium wire.

The electromotive force of the couples was measured by a Wolff potentiometer and a galvanometer, as in the calibration (See Appendix). Each couple was read separately and then the two were connected in opposition and read as a differential couple. The relation

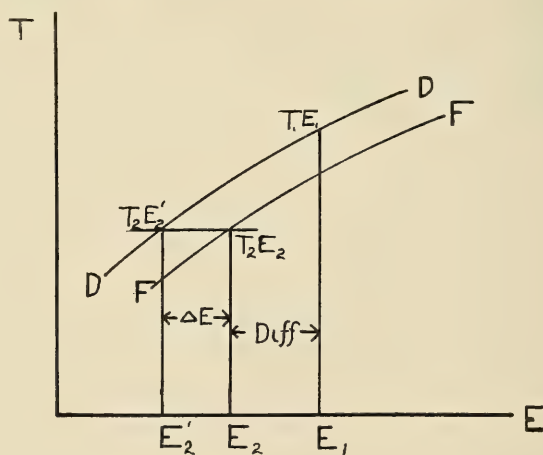


FIG. 5

between this reading and the corresponding difference in temperature is obtained as follows:

Let us call these readings Diff. Let the curve DD (Fig. 5) represent the relation between temperature and electromotive force for couple D , and curve FF , that for couple F . Let E_1 and E_2 be the readings of couples D and F , respectively. The curve DD is expressed by the equation,

$$T_1 = A + BE_1 + CE_1^2$$

and

$$T_2 = A + BE'_2 + C(E'_2)^2$$

then

$$T_1 - T_2 = B(E_1 - E'_2) + C[E_1^2 - (E'_2)^2]$$

now

$$E'_2 = E_2 - \Delta E$$

and $E_1 = E_2 + \text{Diff.}$ ("Diff" is the reading of the differential). Substituting for E_1 and E'_2 above,

$$T_1 - T_2 = B(\text{Diff} + \Delta E) + C(\text{Diff} + \Delta E)(E_1 + E_2 - \Delta E).$$

ΔE is negligible in comparison with $(E_1 + E_2)$ and may be dropped from the last factor.

Manipulation.—The arrangement of the potentiometer circuits is shown in Fig. 6. From the ice bath the couples were connected to two "single-pole double-throw" switches (1 and 2) which were mounted on the same base. Throwing switch No. 1 to the left and No. 2 to the right, couple D could be read. Reversing No. 2 placed F in the circuit. With both switches to the right, the two couples were connected in the circuit in opposition, in their proper order, since D was the hotter couple and therefore had the higher electromotive force.

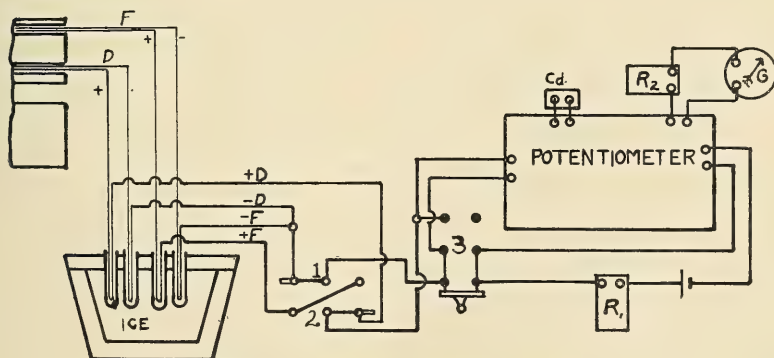


FIG. 6 POTENTIOMETER CIRCUIT

The statement was made above that the heat which was generated at the middle of the coil flowed out along radial lines. This was tested by moving the outer couple F (Fig. 2), back and forth in a longitudinal direction and noting the reading in the various positions. This operation showed that the temperature was constant to 0.3° C. for a distance of 6 or 7 cm. from the middle. As no heat will flow along constant temperature lines, there could be no longitudinal flow of heat in the 12 or 14 cm. in the middle of the test-piece, and hence the assumption is allowable.

The general method of operation was to start the furnace with a rather large current, about 25 amperes, and gradually reduce this, as the furnace approached the temperature desired. This took from three to five hours for the lower temperatures. The storage battery would then be placed in the circuit (see Fig. 4) and the current kept constant for two or three hours more. When the outer couple, F , showed a temperature constant to one-tenth of a degree, indicating equilibrium conditions, readings were taken. The voltage and current readings were taken before and after the temperature readings, in order to be sure there was no change. The temperature readings were taken in the order, D , F , D , $(D-F)$, and D . It will be noticed by referring to Fig. 6, that only one change of either switch No. 1 or No. 2 is necessary to change from any one of the above readings to the next in order. Each cylinder, at the close of the tests on it, was broken across the middle, and r_1 and r_2 carefully measured in the plane in which the temperature readings had been taken.

V. RESULTS

Tables 1 to 4 show the readings and results obtained from the first four cylinders. The curves also show the values of the conductivity at the different temperatures. The tables give, in order, (from left to right), the voltage drop across the furnace E ; the current flowing through the coil I ; the reading of the inner couple (D); the outer couple (F), and of the two connected in opposition as a differential couple $Diff.$, corrected as described above, in micro-volts; the temperature difference, $T_{diff.}$, calculated from the differential reading; the average temperature of the two couples and the conductivity, K . The readings are arranged in the order of increasing

temperatures, although they were not taken in this order in every case. It will be noticed that the conductivity of the two coarser fire-clays was constant, while that of the other two which were of finer structure increased with the temperature.

Table 5 gives the comparative values of the different cylinders in the order in which they were tested. The particular value given for each of the first four was so chosen as to be near the temperature at which the later pieces of the same composition were tested.

The accuracy of the values for K in this work is limited to the accuracy in measuring r_1 and r_2 . The temperature readings are certainly accurate to 1.0°C ., and very probably to 0.5°C . The voltage and current readings are accurate to one per cent. An error may be introduced in the values of r_1 and r_2 because of the uncertainty of the position of the thermo-junction in the hole. If the couple were touching one side of the hole, it would take the temperature of that side, while r_1 and r_2 were always measured to the center of the holes. This error, however, would be a constant factor for the tests on any cylinder, since the couples were never disturbed after they were once placed in a cylinder, until the completion of the tests on that piece. Thus the comparative values of K for any given specimen at different temperatures would not be affected by the values of r_1 and r_2 .

The greatest error is caused by changes of current through the furnace. The supply voltage changed a great deal, and the batteries used were not large enough to maintain the current constant at all times. If the current should change just before a reading was taken, the temperatures would not correspond to the other readings, though they might not be changing at the time. The variation between cylinders of the same composition is probably due to a difference in porosity. An investigation of the effect of porosity as well as composition of substances would, no doubt, lead to more definite results, in regard to a comparison of fire-clays.

TABLE 1

Mark	r_1	r_2	E	I	D	F	Diff	T_{diff}	T_{avg}	K
B	23.5	58.0	27.6	15.4	3677	2067	1597	170.9	362.4	.00209
..			33.6	17.2	4595	2470	2116	223.9	430.6	.00217
..			35.2	17.8	5325	2990	2319	242.6	494.2	.00217
..			38.8	18.7	5928	3257	2657	276.1	537.8	.00221
..			40.9	19.1	6541	3634	2889	297.3	586.6	.00221

TABLE 2

Mark	r ₁	r ₂	E	I	D	F	Diff	T _{diff}	T _{ave.}	K
3	33.8	52.0	30.1	17.8	3700	2919	781	81.3	406.5	.00264
..			36.3	19.8	4687	3621	1066	108.4	493.2	.00266
..			36.0	19.8	4729	3667	1063	108.0	497.7	.00265
..			40.0	20.9	5423	4164	1261	126.0	557.5	.00266
..			40.9	21.1	5514	4232	1285	128.1	565.4	.00270
..			43.9	21.7	6023	4540	1485	146.3	605.7	.00261
..			46.3	22.0	6587	4991	1601	155.4	655.2	.00267
..			47.3	22.3	6626	4992	1635	158.6	657.1	.00263
..			50.6	22.5	7208	5402	1809	172.9	704.6	.00264

TABLE 3

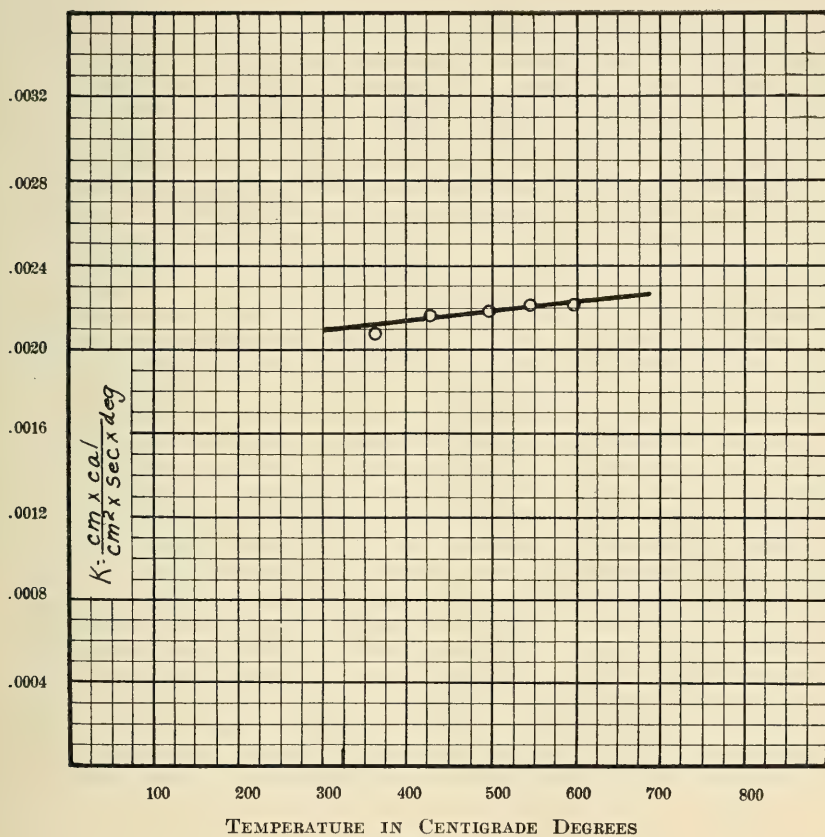
Mark	r ₁	r ₂	E	I	D	F	Diff	T _{diff}	T _{ave.}	K
A	33.3	66.0	39.2	19.9	5197	3190	2001	203.3	496.2	.00245
..			43.8	19.0	5827	3664	2164	216.4	551.6	.00245
..			45.5	20.7	6347	3958	2387	236.0	591.7	.00254
..			49.7	20.4	6924	4232	2693	263.0	633.0	.00246
..			51.7	20.3	7279	4480	2800	271.0	662.1	.00247
..			52.7	20.2	7301	4512	2795	270.4	664.7	.00251
..			52.8	20.5	7377	4598	2782	268.5	672.6	.00251
..			59.7	20.8	8337	5032	3305	312.4	738.0	.00252
..			61.0	21.0	8399	5069	3336	314.9	742.6	.00259
..			61.8	20.6	8591	5191	3403	319.7	757.2	.00254

TABLE 4

Mark	r ₁	r ₂	E	I	D	F	Diff	T _{diff}	T _{ave.}	K
1	23.9	49.3	29.6	16.8	3572	2697	876	91.6	388.2	.00366
..			34.8	18.4	4547	3386	1159	118.5	474.0	.00364
..			42.6	20.5	6031	4335	1678	165.7	596.7	.00355
..			45.2	21.2	6430	4583	1847	180.7	627.4	.00358
..			54.3	22.8	8085	5640	2449	230.2	756.5	.00362

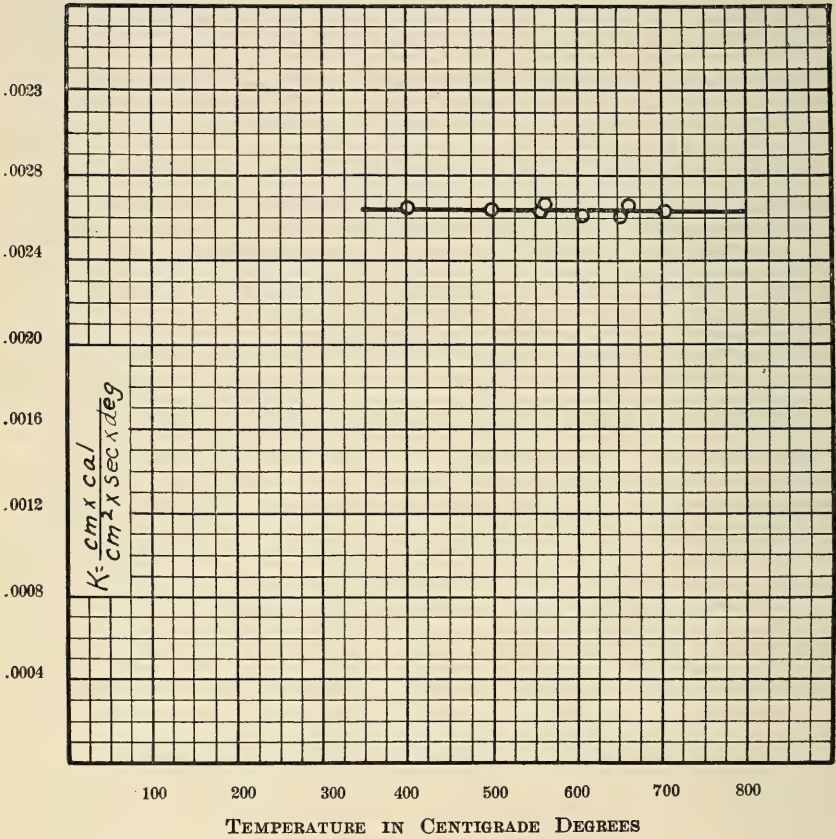
TABLE 5

	Mark	r ₁	r ₂	E	I	D	F	Diff	T _{diff}	T _{ave.}	K
1	B	23.5	58.0	40.9	19.1	6541	3634	2889	297.3	587	.00221
2	3	33.8	52.0	50.6	22.5	7208	5402	1809	172.9	705	.00264
3	A	33.3	66.0	52.7	20.2	7301	4512	2795	270.4	665	.00257
4	1	23.9	49.3	54.3	22.8	8085	5640	2449	230.2	757	.00362
5	3	31.0	48.4	42.0	20.5	5633	4429	1205	119.6	581	.00299
6	A	29.0	56.0	54.0	20.1	8170	5414	2756	259.6	749	.00256
7	3	27.0	49.5	57.0	19.7	8556	6001	2558	237.5	795	.00267
8	1	30.0	51.0	60.5	20.1	8318	5888	2433	227.1	770	.00265
9	B	32.0	51.5	63.0	19.0	8823	6716	2210	202.1	891	.00263
10	B	27.5	46.0	44.0	20.3	6535	4638	1900	185.5	635	.00231
11	A	26.5	61.5	45.0	20.1	7483	4623	2860	275.4	679	.00257



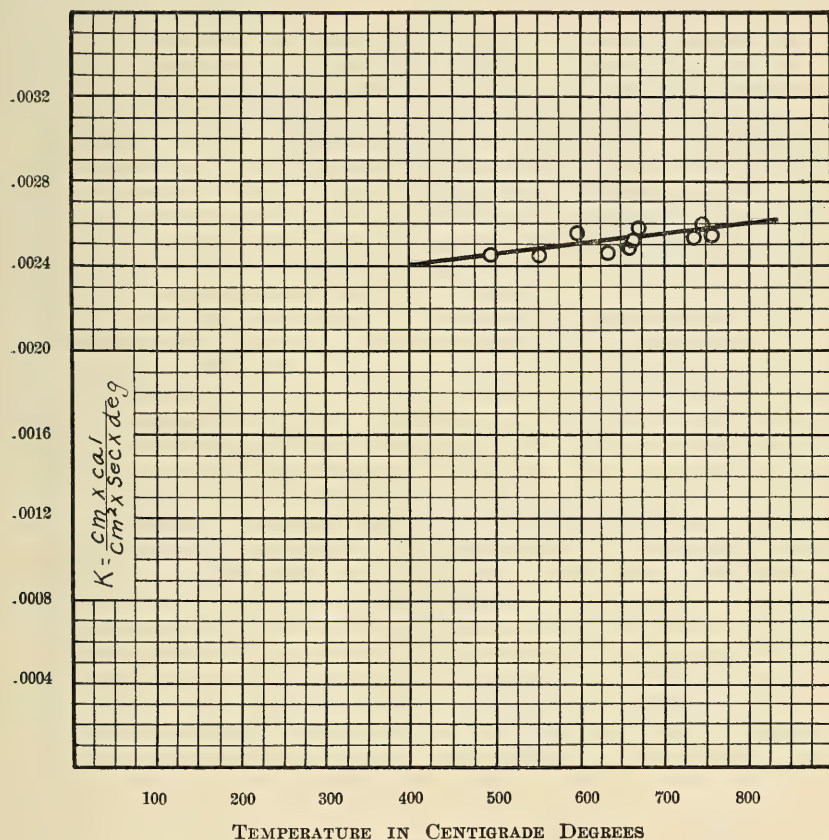
CURVE No. 1

FIG. 7



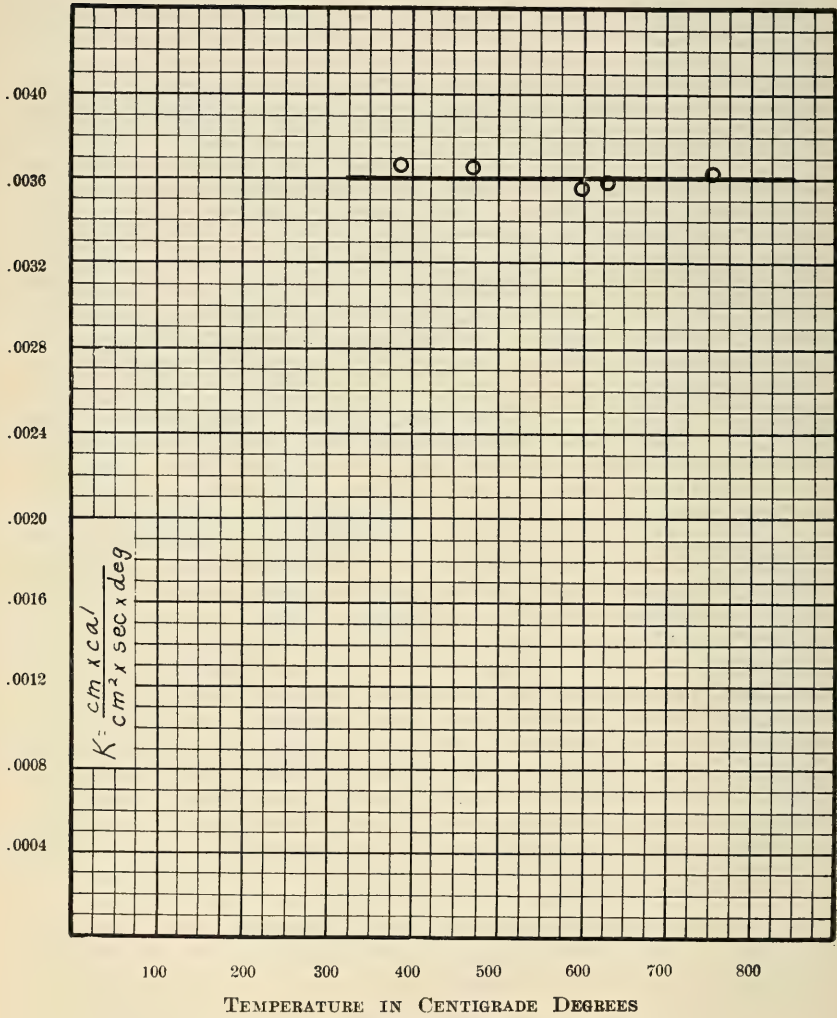
CURVE NO. 2

FIG. 8



CURVE No. 3

FIG. 9



CURVE No. 4

FIG. 10

APPENDIX

The use of thermocouples for measuring high temperatures is no longer a novelty in physical investigations, but the details of the calibration are not generally accessible. Hence the exact method of calibration used in this work has been described at considerable length in this Appendix.

METHOD FOR CALIBRATING THERMOCOUPLES FOR HIGH TEMPERATURE MEASUREMENTS

Since, as a rule, no two thermocouples have the same electromotive force, and since the electromotive force of any couple is appreciably changed by the action of metallic and possibly other vapors at high temperatures, it is necessary to calibrate the couples from time to time. The method described is that known as the *melting point* or *Frankenheim* method.¹ The couple, surrounded by a closed porcelain or fused silica tube, is immersed in the melted metal, and the furnace allowed to cool slowly. Readings of the electromotive force taken at regular intervals will show a steady decrease until the freezing point is reached, remain constant until the metal is nearly all solidified, and will then fall off again. Knowing the temperature at which the metal melts, we can thus determine the value of the electromotive force of the thermocouple corresponding to a definite temperature. Obtaining a number of points in this way by using different metals, a curve may be drawn through them showing the relation between the electromotive force and the temperature for that particular couple.

The Furnace.—Frequent use of this method demands a furnace which may be quickly and readily heated up and easily controlled. The furnace used in this work was a vertical furnace with an inside diameter of $2\frac{3}{8}$ in. and a depth of 6 in. (see Fig. 11). The coil, which was of pure nickel wire about .072 in. in diameter, was first wound in one layer upon a collapsible wooden arbor. The wires were tied together by several longitudinal threads to keep them from springing out when the arbor was removed. A covering of paste, formed of water and a patent mixture, called “magnesite,”² was then applied. After the paste had dried, the coil was placed in a cylinder (also of a magnesite compound) $6\frac{1}{4}$ in. long and just large

¹ (Holborn & Day), Amer. Jour. Science, Vol. 160, p. 171.

² Obtained from Harbison and Walker Refractories Company, Pittsburg.

enough to contain it. The outside diameter was about $4\frac{1}{2}$ in. The arbor was then removed, leaving the coil on the inside of the furnace, which had also been coated with the magnesite paste. This in turn was placed upon a fire-clay disc and surrounded by a cylinder of the same material,¹ the whole being covered with another fire-clay disc, usually in two pieces. The outside dimensions of the whole were about 8 in. in diameter and $9\frac{1}{2}$ in. in height. The space between the magnesite cylinder and the surrounding one of fire-clay was filled loosely with calcined magnesia.²

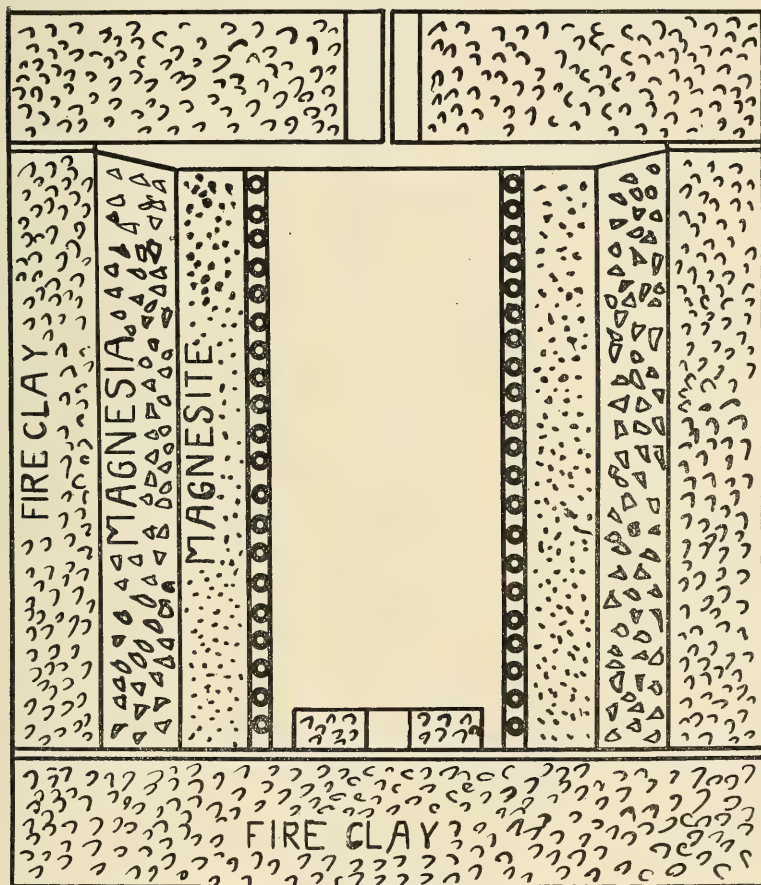


FIG. 11

¹ Obtained from Dental Manufacturing Company, Buffalo, N. Y.

² Obtained from Elmer and Amend, New York City.

To avoid delay, in certain stages of the work, a furnace was used with a cylinder of magnesite instead of fire-clay. This was not so satisfactory, because more heat was lost through the magnesite than through the fire-clay; heavier currents were, therefore, required to maintain the necessary temperatures. With the furnace as described above, a temperature of 1000°C . could be obtained in less than two hours with a current of 25 amperes; and it could be maintained with 19 or 20 amperes.

Heating Circuit.—The arrangement of the heating circuit is shown in Fig. 12. The current was obtained from 110-volt continuous cur-



FIG. 12

rent mains and was regulated by two large Cutler-Hammer rheostats or "theatre dimmers." One of these had a current-carrying capacity of 125 to 50 amperes and a resistance of 4 ohms. The other was specially made and had a fixed resistance of 4 ohms, with 30 amperes carrying capacity, which could be short circuited, and also had a variable resistance of 6 ohms, with 30 to 10 amperes capacity. The low resistance rheostat permitted very small adjustments of current.

Graphite Crucibles.—The charge of metal used was placed in graphite crucibles to a depth of at least 2 in. Fig. 13 shows the shape and size of these vessels. Such crucibles may be purchased from supply houses, but it is preferable to turn them out of graphite rods because the purity of the graphite rod is more certain.¹ The exact dimensions are not specified nor are they necessary so long as they will contain a charge of metal which is large compared with the silica tube surrounding the couple. It is important, however, that the inside of the crucible be tapered so that the charge may be removed. The covers are also of graphite and have a hole in the center for the insertion of the silica tube containing the thermocouple.

Thermocouples.—The thermocouples used in this work consisted

¹ Acheson Graphite Co., Niagara Falls, N. Y.

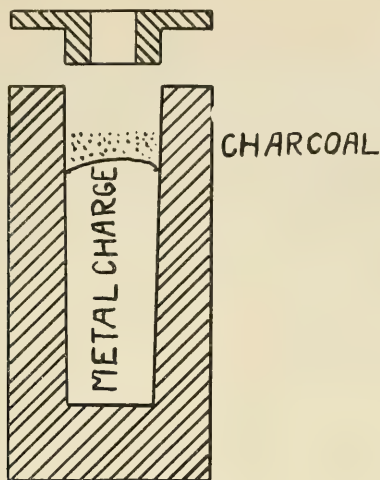


FIG. 13

of one wire of pure platinum and another of 90 per cent platinum and 10 per cent rhodium. The wires were each 0.6 mm. in diameter and 5 ft. long. The two wires were insulated from each other by pieces of very small porcelain tubing which were placed on the platinum-rhodium wire (see Fig. 14). The junction was then placed in a tube of fused silica, closed at the lower end. This tube, containing the wires and capillary porcelain tubing, was thrust into the melted metal to within about $\frac{5}{8}$ in. from the bottom of the crucible.

The protecting tubes of fused silica¹ were about $\frac{1}{4}$ in. in diameter and long enough to extend well out of the furnace. They were supported by a tripod and clamp at the upper end. A broken tube may be readily closed at one end in an electric arc or an oxy-hydrogen flame. Silica tubes as small as 2 mm. inside diameter may be used for this work by dispensing with the porcelain tubing on the platinum-rhodium wire, and separating the wires with strips of mica. This arrangement has considerable advantage, enabling one to get a much better curve; a smaller charge of metal can also be used. It is, however, not advisable to use the smaller tubes where a number of couples are to be calibrated, and where time is of importance, as it is difficult to insert the wires in the tube and keep them separated.

Cold Junctions.—The other ends of the wires were soldered to copper wires and kept at 0° C. The arrangement of these junctions

¹ Eimer and Amend, New York City.

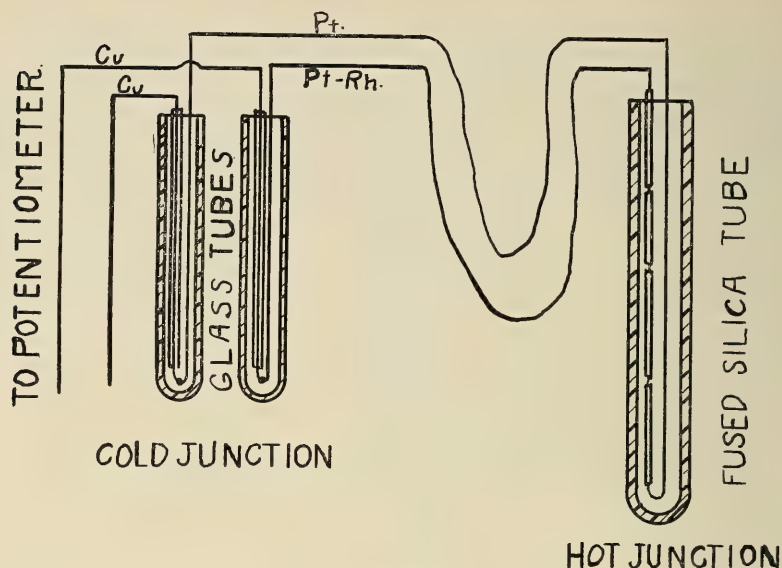


FIG. 14

(see Fig. 14), was similar to that of the hot junction except that glass tubing was used in the place of the quartz and porcelain. They were kept at the ice point by placing them through the lid of a double-walled bucket, which contained a mixture of ice and water. This bucket was packed with sawdust between the two walls.

Metals Used for Fixed Points.—The metals used for calibrating the couples were zinc in an oxidizing atmosphere, melting at 419° C.; silver in a reducing atmosphere, melting at 961.5° C.; and copper in a reducing atmosphere, melting at 1084° C. These values of their melting points are the ones found by Holborn and Day, 1900, and are at present accepted by the German Reichsanstalt. Later values found by Day and Clement are somewhat lower, being $418.5^{\circ} \pm .1$; $958.3 \pm .5$; and $1081.0 \pm .5$ respectively.¹ The charges of silver and copper were covered with powdered charcoal which was of a very pure grade. This was done because the values given above for these two metals were obtained in a reducing atmosphere.

Other metals which may be used are cadmium, 322° C.; and gold 1063° C. The melting point of cadmium is somewhat low for a platinum-rhodium couple. Above 1100° , nickel melting at 1435° , iron melting at 1505° , and platinum melting at 1720° , may eventually

¹ Amer. Jour. Science, Vol. XXVI, Nov., '08.

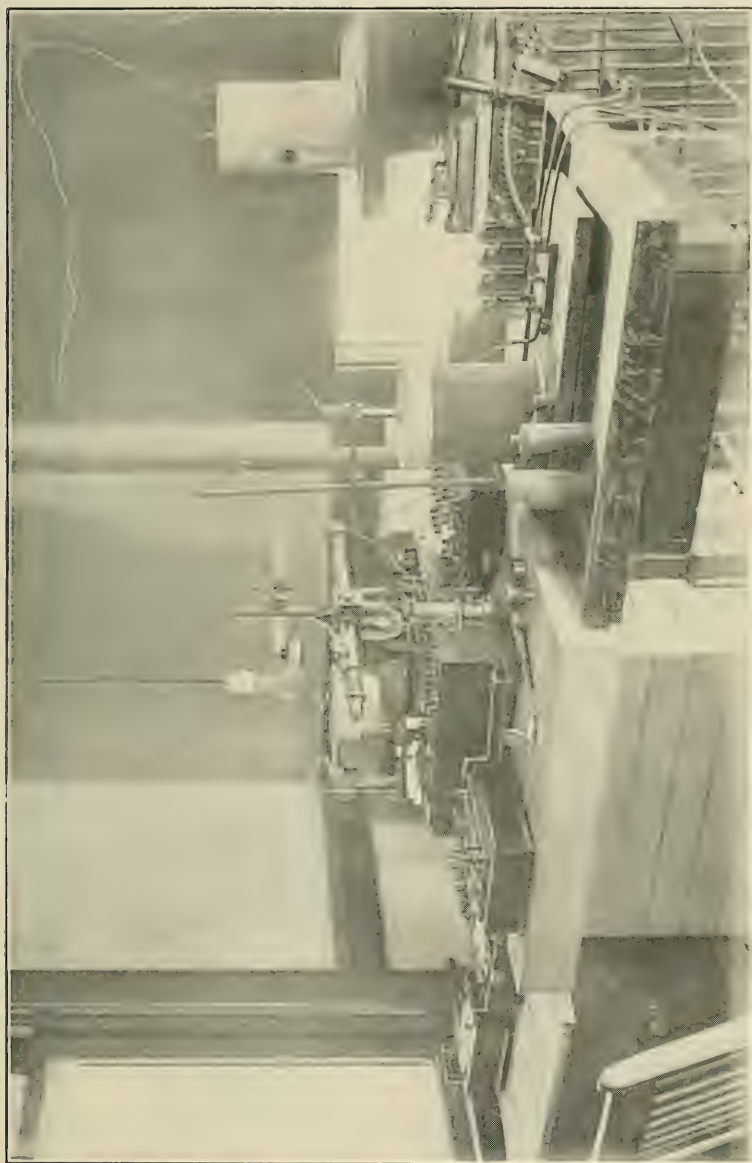


FIG. 15 SHOWING CALIBRATION FURNACE AND POTENTIOMETER

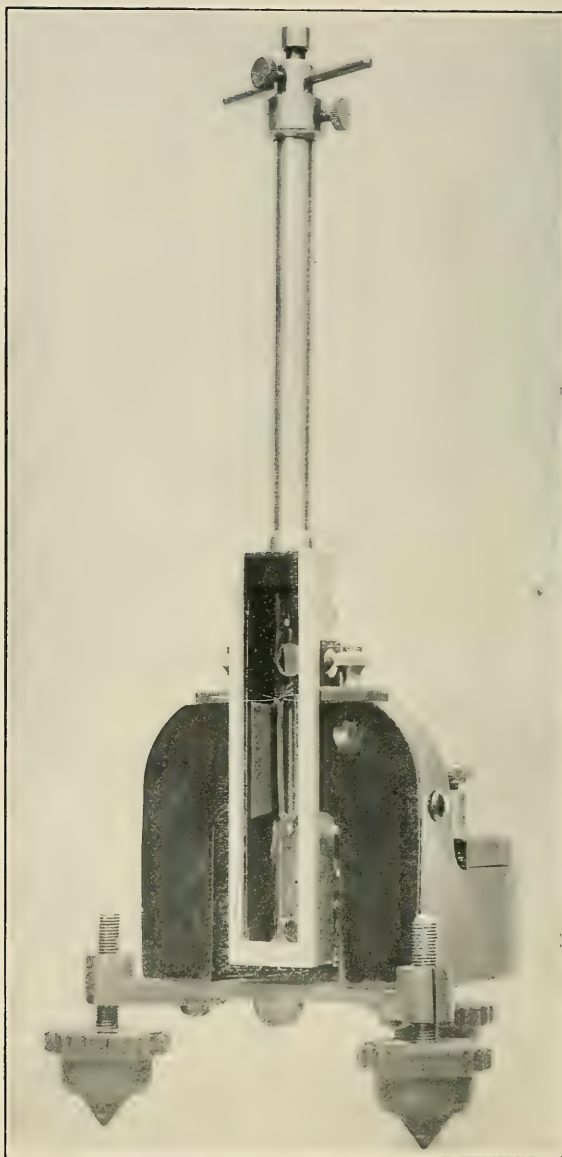


FIG. 16 SPECIAL GALVANOMETER MADE FOR USE WITH
THERMOCOUPLES

be available for fixed points, although it is not advisable to use any point above the copper point until the gas thermometer scale has been established above 1100° . A number of metals are unavailable for getting a fixed point on account of under-cooling.

It is of importance that the metals used for fixed points be of the highest purity, since any impurity alters the melting point.

Typical Set of Readings.—Below is given a typical set of readings taken with couple *F* (see p. 10), at the zinc melting point. The readings are in micro-volts or .000001 volt. The first column was taken with 8 amperes flowing through the furnace. After the zinc had solidified, the current was increased to 17.5 amperes, and as the zinc melted, the readings in column two were taken. The readings were taken regularly at intervals of 30 seconds.

8 Amperes		17.5 Amperes
3461		3404
3440		3412
3431		3415
3430		3418
3429		3421
3429		3423
3429	Freezing Point 419° C.	3425
3429		3426
3429		3427
3429		3428
3429		3428
3428		3429
3428		3429
3426		3435
3420		3460
3414		3490
3400		

Melting Point
419° C.

It may readily be seen from these curves that the transition points can be fixed better from the cooling curves than from the melting curves, because the bend of the curve is sharper and the flat part of the curve is better defined. Hence the cooling curve is the one used. It is much more definite and may be repeated, while the heating curve is often a little below the actual temperature, due to the lag in the charge and conduction of heat by the tubes.

Potentiometer and Galvanometer.—The electromotive force of the couples was measured with a Wolff potentiometer and galvanometer; a combination of the compensation and galvanometer methods being used (see Fig. 17). The Wolff box was connected in series with an adjustable resistance, R_1 , of a little over 5000 ohms, and a single storage cell. As the resistance of the potentiometer was 15 000 ohms, the current could then be adjusted to exactly .0001 ampere. This

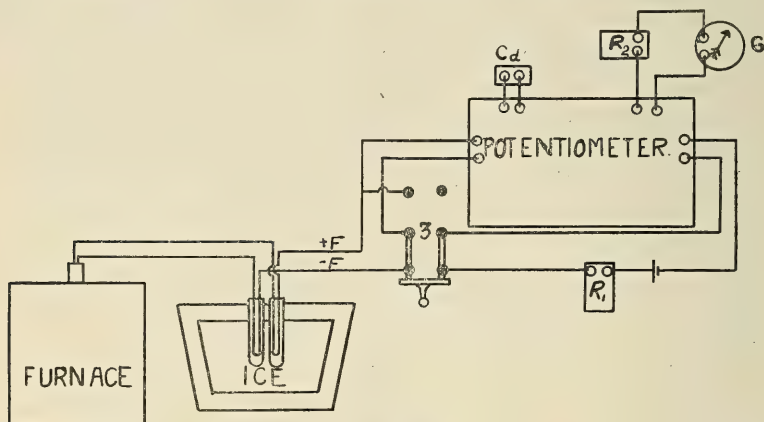


FIG. 17

was done by connecting a standard cell, ($Cd.$), of 1.0197 volts, across a resistance in the box of 10 197 ohms, and adjusting the series resistance, R_1 , until the galvanometer, G , showed no deflection on closing the circuit. A reading of one ohm on the box then corresponded to .0001 volt or 100 micro-volts. As the smallest divisions of the box are 0.1 ohm, this gave a sensibility of 10 micro-volts, or about 1° C .

The galvanometer ¹ had a period of four seconds on open circuit and a sensibility of 2.85 micro-volts or 210 megohms. Its resistance was 230 ohms. It was used with a telescope and scale at a distance of about 150 centimeters.

A small resistance, R_2 , was connected in series with the galvanometer, and this was adjusted so that the last dial on the Wolff box corresponded to a deflection of ten divisions of the scale. This increased the sensibility of the apparatus tenfold, as one scale division thus corresponded to 1 micro-volt or about 0.1° C . This adjustment was accomplished by first closing the battery circuit, setting the

¹ D'Arsonval type made especially for this work by Leeds & Northrup Co.

potentiometer on zero, and short-circuiting the thermocouple circuit. Such a value of R_2 could then be found that a movement of one division of the next to the last dial on the box, would give a deflection of exactly one hundred scale divisions. Of course as the setting of the box is increased or diminished, R_2 would have to be decreased or increased a corresponding amount, to keep the sensibility constant.

Scale and Telescope.—The scale used with the galvanometer had divisions about 0.6 mm. in length. One half of the scale was marked with red and was numbered from 800 at the end to 1000 or 0 at the center. The other half was black and was numbered from 0 at the center to 200 at the other end. The galvanometer was so connected that deflections toward the black figures indicated an addition to the potentiometer reading, and those toward the red figures a subtraction from it. The advantage of having the red scale read backwards, that is from 1000 to 800, is that negative deflections are already subtracted when read. For example, a negative deflection of 15 divisions would read 985. This, besides being a great convenience, also reduces to a minimum the chance of error in subtracting the galvanometer reading from that of the potentiometer.

Telescope.—The telescope used was a Hartmann and Braun instrument with horizontal and vertical tangent screw adjustments. These adjustments are a great convenience, the horizontal adjustment for setting the scale to zero being almost a necessity.

Manipulation.—When readings were to be taken at regular intervals as in the above set, the current was first adjusted, as described above, by comparison of the potentiometer with the standard cell. The galvanometer was then short-circuited through the Wolff box by the "double-pole double-throw" switch shown in Fig. 17. In the position shown, this switch closes the main potentiometer circuit with the storage cell, with the right hand blade, and connects the thermocouple to the potentiometer with the left hand blade. The pole on the left was shortened so that the right side made contact first, thus closing the main circuit before the galvanometer circuit was closed. By reversing this switch, the battery circuit is opened and the galvanometer circuit closed through the potentiometer only. The galvanometer scale was set at zero before each reading with this switch in the reverse position. This eliminates errors due to stray electromotive forces which may be in the circuit. The switch is then again changed, and the dials on the box adjusted until the galvanometer is as near

zero as is convenient. Care is then taken to get the reading on the scale at the exact end of the interval, and adding (or subtracting) this reading to that indicated on the box. It is readily seen that when using the galvanometer reading in addition to that of the potentiometer, it is more convenient to have a box that may be adjusted by steps, rather than by a continuous contact along the winding.

External Influences.—Great care had to be taken with this arrangement of apparatus to avoid magnetic disturbance and electric leakage from the power circuit. Little trouble was experienced in cold dry weather with electric leakage, but during the warm moist weather of summer, it sometimes seemed almost impossible to avoid leakage.¹

Formula for Calculating Temperature.—The formula which was used for calculating the temperature is $t = a + be + ce^2$, e representing micro-volts. Substituting the values for t and e obtained from the zinc, silver and copper points, we have three equations as follows:

$$t_1 = a + be_1 + ce_1^2$$

$$t_2 = a + be_2 + ce_2^2$$

$$t_3 = a + be_3 + ce_3^2$$

The values of e_1 , e_2 and e_3 obtained for couple F' used in the thermal conductivity work (see p. 10), were 3429, 9101 and 10534, respectively. Solving the above equations for a , b , and c , and substituting for t_1 , t_2 , t_3 , e_1 , e_2 , and e_3 ,

$$a = 46.41$$

$$b = .11356$$

$$\text{and } c = -1.4300 \times 10^{-6}$$

The temperatures measured by this couple are found by the equation

$$t = 46.41 + .11356 e - .00000143 e^2.$$

This parabolic equation is the one generally accepted at the present time for the platinum alloy couples when the cold junction is at 0° , although it will not hold below 250° C. , and can be used only approximately below 350° C. If the cold junction is above the ice point, a correction must be added to the observed temperature, equal to 0.5 times the temperature of the cold junction in Centigrade degrees.

$t = t(\text{obs}) + 0.5 \times \text{temperature of cold junction.}$ The possible accuracy of the above equation is about 0.5° C. , between 350° and 1100° C. The probable accuracy of the temperatures as measured

¹ Discussion by W. P. White, Physical Review, 1907.

above is about 1° over the same range, though the sensibility is 0.1° C.

Other equations have been offered by Regnault, Avenarius and Tait, Stansfield, and others, but are not used at the present time. References ¹ on thermal electricity are given below.

Galvanometer Method.—For work which does not require such a high degree of accuracy, it is more convenient to use a galvanometer alone for reading the electromotive force. With a galvanometer of about 400 ohms resistance, by taking proper precautions, the readings are reliable within 5° C. up to 1100° C.

Lower Temperatures.—For temperatures below 400° , a copper-constantan couple will be more satisfactory, as it has about four times the thermo-electric power of the platinum-rhodium couple. It may be used from 0° to 500° .

Contamination.—Great care must be taken to avoid contamination of the platinum couples, as they are very readily attacked by metal vapors at the higher temperatures. The readings of the couple will be lowered by contamination. The couple can be restored only by removing the contaminated portion. With care, however, contamination may be avoided and the readings of the couple kept constant. The two couples used in the conductivity work described on p. 10 did not change within the sensibility of the measurements during four months of almost continuous use.

¹ A Text-Book of Physics (Watson), p. 714.

High Temperature Measurements (Le Chateller), p. 120.

A. Stansfield on Some Improvements in the Roberts-Austin Recording Pyrometer, Phil. Mag. July, 1898, p. 73.

Tait, P. G.—Collected Papers, Vol. I, Cambridge University Press.

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

- Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (Out of print.)
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BULLETIN NO. 37

UNIT COAL AND THE COMPOSITION OF COAL ASH

BY

S. W. PARR

AND

W. F. WHEELER



UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No 37

AUGUST 1909

UNIT COAL AND THE COMPOSITION OF COAL ASH

BY S. W. PARR, PROFESSOR OF APPLIED CHEMISTRY

AND

W. F. WHEELER, FIRST ASSISTANT, DEPARTMENT OF CHEMISTRY,
ENGINEERING EXPERIMENT STATION

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I. INTRODUCTION¹

It was recognized at the very outset of these experiments on coal, which were begun in the Laboratory of Industrial Chemistry, University of Illinois, about the year 1897, that much value would attach to any device or method which would make it possible to study the properties, composition, heat values, etc., of the pure coal substance as distinct from the non-coal material with which it is associated. While much data of a general nature accumulated from year to year, having more or less bearing upon this subject, it was not until recent months that a definite study of the problem was undertaken. It is the purpose of this paper to present the results of these investigations upon the properties and more definite determination of actual or unit coal. By unit coal is meant the organic material which is involved in combustion as apart from the mineral constituents which are the extraneous and variable accompaniments of the actual or unit coal.

II. HISTORICAL REVIEW

A number of investigators have worked on various phases of this topic. Lord and Haas, who were no doubt the first in the field, have developed the idea that in any given type of coal, or perhaps, less broadly, in any given deposit of coal, there exists an initial substance, with certain uniformities as to calorific value, which might make it possible to calculate the heat units for any sample whose source as to locality was known.

From numerous analyses of Pennsylvania and Ohio coals, Lord and Haas draw a comparison between the heat values as derived by Du Long's formula, the Mahler calorimeter, and those calculated from unit value which they designate as H , and describe as being the value for the ash, water and sulphur-free substance. They find the sulphur to be a disturbing element and correct for it in a partial manner only. However, they state as their conclusion that "On comparing the results, seam by seam, it would appear

¹Credit is due Mr. W. F. Wheeler for the greater part of the work embodied in this bulletin. Mr. Wheeler died November 18, 1909.

that the actual coal of a given seam, at least over considerable areas, may be regarded as essentially of uniform heating value.”¹

The expression “actual coal” presumably refers to this same initial or unit substance free from extraneous matter, such as ash, moisture and sulphur. The same idea is evidently intended in the quotation below, though the same qualification as to “actual coal” is not used, thus, “The results of our tests seem to indicate the interesting conclusion that the character of a coal seam, so far as its fuel value is concerned, is a nearly constant quantity over considerable areas. The determination of the value for seams would be of great use, as the rapid proximate analysis, or, for that matter, merely the determination of ash and moisture in low sulphur coals, would be sufficient to grade coals of the same vein. Of course, it is dangerous to argue from so few samples, but the proposition seems reasonable. At least, we hope that further work may confirm these conclusions.”

Kent, in discussing this paper, in the same volume, page 946, says, “The conclusions of the authors that the ‘actual’ coal (moisture and ash excluded) of a given seam over considerable areas, may be regarded as of uniform heating value, is one of great practical importance. I have held the same opinion tentatively for a long time....”

Contemporaneous with the work of Lord and Haas was that of W. A. Noyes.² As a result of 21 calorimetric determinations on Indiana and Pittsburgh bituminous coals, he says, “The heating effect may be found, in all cases examined, with a maximum error of 2 per cent, by the following rule: Subtract from 100 the per cents of moisture, ash, and one half the per cent of sulphur, and multiply the remainder by 80.7. The product will be the heating effect of the coal burned to vapor of water, expressed in calories.”

Whatever value may have attached to these propositions, the matter seems to have lain more or less dormant until the subject

¹Trans. Am. Inst. Min. Eng. 27; 259, 1898.

²Jour. Amer. Chem. Soc. 20; 285, 1898.

was brought again to the surface by Mr. A. Bement, who has in numerous articles insisted upon its great practical value, as, for example, referring to the advantage of having certain units of reference, he says, "The possibility of the more extended use of constants is presented and the author urges the feasibility of considering the pure coal compositions as constants for a coal seam or particular locality of such seams. This possibility has been suggested, principally by the fact that the heating power of the pure coal from a general locality does not vary over greater limits than that of the calorimetric method, and he has been able to employ it as a constant in calculating the heating power of dry and moist coal, having determined only moisture and ash, and obtained results that check with calorimetric determinations made on the same samples. The author, however, does not claim originality in this observation, but does insist that the use of such constants is of advantage. . . . This view concedes that coal from a certain locality or seam does not vary in quality, but that the variation is due to the presence of ash and moisture which are impurities associated with the coal."¹

In a subsequent paper,² he argues for the same constancy of values when referred to the pure coal basis. These considerations have, no doubt, led Mr. Bement and others to adopt the term "pure coal" as expressive of this idea of constancy in the "ash and water-free" substance, in addition to the fact of its being a more compact and convenient term to use.

In all of these discussions relating to the uniformity of values for the actual coal, it is evident that if there are any constituents that fail of recognition to the extent that they are not included among the factors for mineral or non-coal material, but on the contrary, are included in the actual coal substance, then the question arises as to whether we yet have a fair basis of reference for drawing conclusions as to the constancy or the degree of agreement which we may properly credit to the actual coal constituent.

¹Jour. Am. Chem. Soc. 28; 636.

²Jour. Western Society of Engineers 11; 757.

For example, the coals of the Mississippi Valley may have as high as 4 or even 8 per cent of sulphur. Indeed, variations of 1 to 3 per cent may be possible within the product from the same mine, especially where the washing of the coal is in vogue. Now if this variable is counted as part of the "actual coal," it by so much prohibits any uniformity of heat values being credited to this hypothetical substance we call "unit coal." This phase of the subject was touched upon in the discussion¹ accompanying the paper by Mr. Bement already mentioned. It was there urged that not only the sulphur, but certain volatile constituents were present which escaped determination as part of the ash, and were, therefore, included in the actual coal, thus introducing a variable which prevented accurate study of that substance. Shortly afterward, analytical evidence in support of this idea was developed by Mr. Wheeler,² and the results of his investigation were published in 1908. The essential point developed in that work was the evidence of the existence of a non-coal constituent which by the ordinary methods of analysis not only escapes recognition and measurement, but is counted as part of the true coal substance. This is the water of hydration or other volatile matter chemically combined with the mineral or ash substance in such a manner as to be driven off only at a red heat. For example, if the shale content of the ash has 8 per cent combined water, and the same is not counted with the ash but as part of the "volatile combustible," here is a variable which by so far keeps us from coming at the correct value for the actual or unit coal. Similar variables would accompany the presence of gypsum whose water of crystallization in the process of analysis would take its place as part of the pure coal substance. Calcium carbonate also would afford a similar variable in so far as it would lose carbon dioxide in the process of analysis. It should be noted here that Taylor and Brinsmaid have proposed a graphical method for arriving at unit coal values which, though empirical and consequently indi-

¹Parr; Jour. Western Society of Engineers 11; p. 762, 1906.

²Trans. Am. Inst. Min. Engs., Vol. 38, p. 621, 1908.

rect in character, is very ingeniously devised and no doubt is of much practical value.¹

III. EXPERIMENTAL DATA

It is the purpose of this paper to present the results of our own investigations, together with such applications as the data at hand will permit, in the hope that the facts presented may indicate the possibility of arriving directly at the determination of all of the non-coal or mineral constituents, including those more volatile mineral compounds which have heretofore been associated in analytical processes with the fuel. The fact should be especially emphasized that it has been the purpose of the investigation to arrive, first, at an exact determination of the inorganic component of the coal as distinct from the organic material, and, second, to study the constancy of composition of this organic substance as indicated by its heat content. Only in this manner can we arrive at a conclusion as to whether or not it has properties which will warrant its use as a fuel unit. Manifestly, therefore, the sulphur should be excluded from this unit. In so far as sulphur occurs in the form of iron pyrites, and this includes the major part, it is extraneous in character and bears no constant ratio to the amount of organic matter present.

For the purpose of illustrating by specific instances the effect of including such variable constituents as sulphur, etc., in the combustible matter, instead of in the ash, and so allowing them to augment falsely the actual coal substance, the following experimental procedure was followed:

A given sample of the coal was separated into two divisions of high and low ash content in a solution of zinc sulphate of 1.35 specific gravity, whereby that part of the coal with low ash and less pyrites was separated by floating from the heavier particles with higher ash and more sulphur, the latter sinking to the bottom. Now, upon the hypothesis that the "actual coal" in these

¹Jour. Ind. and Engrg. Chem. Vol. 1, Feb. 1909.

two divisions of the same sample should have the same heat value, the subjoined table is arranged to show what widely divergent values may be indicated by reason of different methods of arriving at the "actual coal" constituent. If everything excepting the ash as weighed and the moisture be credited to this material, there will result unit values, as shown under column (a) of the subjoined Table 1, which is the "pure coal" of Mr. Bement. If we take out the heat due to sulphur, and correct the remaining value for ash as determined, plus moisture, plus all of the sulphur, there will result values as shown in column (b), which would be the results as derived by means of the method of Lord and Haas. If we calculate the indicated values to the material as free from ash and moisture and correct also for one-half of the sulphur, there will result values, as shown under column (c), which would conform to the method as suggested by Dr. Noyes.

In column (d) we have results from the method of calculation which subtracts the heat due to the sulphur, corrects the ash for the sulphur, and also adds a uniform amount for hydration or volatile inorganic matter, amounting to 8 per cent calculated upon the corrected ash free from iron pyrites, assuming all of the sulphur to be in that form. A tabular statement, therefore, for these four different methods of calculation would be as follows:

(a) According to Bement

$$\begin{array}{r} \text{B. t. u. as indicated} \\ \hline 1.00 - (\text{Moisture} + \text{Ash as weighed}) \end{array}$$

(b) According to Lord and Haas

$$\begin{array}{r} \text{B. t. u.} - 4050 \text{ S} \\ \hline 1.00 - (\text{Moisture} + \text{Ash as weighed} + \text{Sulphur}) \end{array}$$

(c) According to Noyes

$$\begin{array}{r} \text{B. t. u. as indicated} \\ \hline 1.00 - (\text{Moisture} + \text{Ash as weighed} + 1/2 \text{ Sulphur}) \end{array}$$

(d) According to Parr and Wheeler

$$\begin{array}{r} \text{B. t. u.} - 5000 \text{ S} \\ \hline 1.00 - [\text{Moisture} + \text{Ash} + 5/8 \text{ S} + .08 (\text{Ash} - 10/8 \text{ S})] \end{array}$$

TABLE 1
COMPARATIVE VALUES OF "ACTUAL COAL"

Tab. No.	Lab. No.	DESCRIPTION OF SAMPLE	OVEN-DRY COAL				HEAT VALUE OF "ACTUAL COAL" AS CALCULATED BY DIFFERENT METHODS			
			Ash	Sul.	Iron	B. t. u.	(a) Non-coal as Ash only (uncorrected) Ref. to Indicated B. t. u.	(b) Non-coal as Ash (uncorrected) + Sulphur Ref. to B. t. u. — 4050 S.	(c) Non-coal as Ash + $\frac{1}{2}$ Sulphur Ref. to B. t. u. as Indicated	(d) Non-coal as 1.08 X Ash + 22/40 S. Ref. to B. t. u. — 5000 S.
1	6130 6131	Sangamon Co., Ill., Lump Coal:								
		(a) Untreated.....	11.66	5.99	3.38	12356	13987	14709	14477	14331
		(b) Floated, Sp. Gr. less than 1.35.....	6.12	3.20	.65	13300	14164 + 177	14523 — 186	14412 — 65	14340 + 9
2	6122 6123	Sangamon Co., Ill., Screenings:								
		(a) Untreated.....	18.21	4.25	2.37	11478	14031	14709	14428	14442
		(b) Floated, Sp. Gr. Less than 1.35.....	8.13	2.95	.70	13043	14192 + 161	14534 — 175	14407 + 21	14392 — 50
3	6290 6121	Williamson Co., Ill., Washed Nut:								
		(a) Untreated.....	12.83	1.85	1.09	12523	14361	14593	14519	14603
		(b) Floated, Sp. Gr. less than 1.35.....	4.01	1.39	.54	13929	14509 + 148	14664 + 71	14615 + 96	14602 — 1
4	6129 6128	LaSalle Co., Ill., Washed Screenings:								
		(a) Untreated.....	10.05	3.43	2.32	12885	14316	14616	14602	14566
		(b) Floated, Sp. Gr. less than 1.35.....	3.94	2.33	1.29	13922	14487 + 171	14754 + 138	14680 + 78	14615 + 49

TABLE 1

COMPARATIVE VALUES OF "ACTUAL COAL"—(Continued)

		DESCRIPTION OF SAMPLE	OVEN-DRY COAL				HEAT VALUE OF "ACTUAL COAL" AS CALCULATED BY DIFFERENT METHODS			
Tab. No.	Lab. No.		Ash	Sul.	Iron	B. t. u.	(a) Non-coal as Ash only (uncorrect- ed) Ref. to Indicated B. t. u.	(b) Non-coal as Ash (uncor- rected) + Sulphur Ref. to B. t. u. — 4050 S.	(c) Non-coal as Ash + $\frac{1}{3}$ Sul- phur Ref. to B. t. u. as Indicated	(d) Non-coal as $1.08 \times$ Ash + $22/40$ S. Ref. to B. t. u. — 5000 S.
5	6132	Vigo Co., Ind. Nut:	16.84	7.62	5.17	11790	Diff.	Diff.	Diff.	
	6133	(a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	4.27	3.08	1.06	13870	14170 14478 + 308	15230 14836 — 394	14858 14725 — 133	14698 14638 — 60
6	6135	Sullivan Co., Ind. Lump:	6.11	3.37	2.24	13664	14551	14944	14819	14741
	6134	(a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	2.53	1.29	.36	14259	14624 + 73	14771 — 173	14820 + 1	14700 — 41
7		Franklin Co., Ill., Face sample:								
	471	(a) Sp. Gr. greater than 1.35.....	18.00	.57	Not Det.	11639	14194	14236	14244	14467
	463	(b) Sp. Gr. less than 1.35...	4.64	.54		13765	14435 + 241	14492 + 229	14476 + 232	14513 + 46
8		Franklin Co., Ill., Face sample:								
	536	(a) Sp. Gr. greater than 1.35.....	14.43	1.45	"	12142	14190	14495	14310	14433
	464 }	(b) Sp. Gr. less than 1.35...	3.83	.71	"	13918	14472 + 282	14550 + 60	14525 + 215	14541 + 108

TABLE 1

COMPARATIVE VALUES OF "ACTUAL COAL"—(Concluded)

Lab. No.	Lab. No.	DESCRIPTION OF SAMPLE	OVEN-DRY COAL				HEAT VALUE OF "ACTUAL COAL" AS CALCULATED BY DIFFERENT METHODS			
			Ash	Sul.	Iron	B. t. u.	(a)	(b)	(c)	(d)
							Non-coal as Ash only (uncorrected) Ref. to Indicated B. t. u.	Non-coal as Ash (uncorrected) + Sulphur Ref. to B. t. u. — 4050 S.	Non-coal as Ash + $\frac{1}{3}$ Sulphur Ref. to B. t. u. as Indicated	Non-coal as $1.08 \times$ Ash + 22/40 S. Ref. to B. t. u. — 5000 S.
9	472	Perry Co., Ill., Face sample:					Diff.	Diff.	Diff.	Diff.
		(a) Sp. Gr. greater than 1.35.....	22.17	1.15	"	10922	14033	14183	14136	14405
	465	(b) Sp. Gr. less than 1.35....	4.22	.86	"	13763	14369 + 336	14464 + 281	14434 + 298	14446 + 41
10	537	Perry Co., Ill., Face sample:								
		(a) Sp. Gr. greater than 1.35.....	9.52	.65	"	12947	14309	14384	14360	14452
	466	(b) Sp. Gr. less than 1.35....	2.66	.74	"	13985	14367 + 58	14430 + 46	14422 + 62	14421 - 31
11		Williamson Co., Ill., Face sample:								
	473	(a) Sp. Gr. greater than 1.35.....	17.75	1.15	"	11766	14306	14451	14405	14599
	467	(b) Sp. Gr. less than 1.35....	4.08	.99	"	13942	14535 + 229	14644 + 193	14617 + 212	14615 + 16
12		Williamson Co., Ill., Face sample:								
	538	(a) Sp. Gr. greater than 1.35.....	18.28	1.37	"	11731	14355	14531	14475	14667
	468	(b) Sp. Gr. less than 1.35....	4.34	1.07	"	13970	14604 + 249	14725 + 194	14694 + 219	14690 + 23

The method of deriving a formula embodying the conditions prescribed under (*d*) would be as follows:

First, with reference to the subtraction of the heat due to the sulphur. It should be borne in mind that the purposes of this study are (1), to arrive at the actual weight of unit coal as represented by the expression 1.00 — (all non-coal constituents), and (2) to derive the actual heat per unit weight to be credited to this material, by dividing the indicated heat for this substance by the weight which produces it. Hence, for this particular purpose, the sulphur must be eliminated, both as to its heat value and as to its weight in the material whose value is sought for. This procedure may not suit the purpose of the engineer who has in mind only the available heat without reference to its source, but that is a matter quite apart from the facts which it is the purpose of this discussion to establish.

Second, the expression 5000 S has been used as indicating the heat due to the combustion of the sulphur, for the reason that the value 4050 S, as used in formula (*b*) represents the heat of combustion for pure sulphur, while the heat of combustion of sulphur in the form of pyrites, FeS_2 , combines also the heat of formation of iron oxide, Fe_2O_3 . It is the resultant value, therefore, of the several reactions involved that is desired.

According to the direct tests by Somermeier,¹ in the combustion of coal with known weight of iron pyrites, the indicated heat per gram of sulphur so combined is 4957 calories. In calculating heat values, the correction introduced for the combinations resulting from calorimeter reactions as compared with open-air combustion is 2042 calories per gram of pyritic sulphur; hence 4957 — 2042 or 2915 calories (5247 B. t. u.) represents the heat due to the burning of one gram of sulphur in pyritic form instead of 2250 calories (4050 B. t. u.), the amount which would be credited to sulphur in the free condition. A strict application of these values, therefore, would call for a correction of 5247 S, as representing the heat to be subtracted for the sulphur. This,

¹Jour. Am. Chem. Soc. Vol. 26, p. 566.

however, would imply that all of the sulphur is in the pyritic form. Since a certain portion of the sulphur is always present in organic or other form of less heat-producing capacity, it is deemed more nearly correct to use an even factor of 5000 as representing the heat to be credited to unit amounts of the total sulphur present.

The factors for the divisor in the formula under (*d*) are derived as follows:

The atomic ratio of iron to sulphur in iron pyrites (FeS_2) is 56 : 64; that is, $7/8$ of the total sulphur is the equivalent of the iron present as Fe.

The atomic ratio of the oxygen of the ash, combined as Fe_2O_3 to the total sulphur which it replaces is 48:128; that is, $3/8$ of the total sulphur is the equivalent of the oxygen present in the ash, combined as Fe_2O_3 , hence the ash as weighed may be corrected for the iron pyrites FeS_2 burned to Fe_2O_3 , by subtracting from the ash $10/8$ of the weight of the sulphur as determined. This remainder, therefore, is considered as the shaley and carbonate constituent upon which the 8 per cent of water of hydration, carbon dioxide, etc., are calculated. The expression for the total non-coal substance then becomes

Non-coal = Moisture + Ash as weighed + $5/8$ S + .08 (Ash - $10/8$ S).

Clearing of fractions and combining,

Non-coal = Moisture + 1.08 Ash + $21/40$ S.

In this expression the factor $21/40$ S can not be further simplified by making it $1/2$ S, for the reason that our correction for sulphur is already too small by that part of the organic sulphur not covered by the addition to the ash value of $3/8$ of the total sulphur indicated in the original formula. On the contrary, we shall be approaching nearer the truth by increasing slightly the sulphur correction, which may be done with convenience in calculating, by making this factor read $22/40$ S or $1/2$ S + $1/20$ S.

Hence the simplification of the entire formula under (d) would be

B. t. u. or unit coal =

$$\frac{\text{Indicated B. t. u.} - 5000 \text{ S}}{1.00 - (\text{Moisture} + 1.08 \text{ Ash} + 1/2 \text{ S} + 1/20 \text{ S})}$$

Since the analytical values given in the table are based upon the coal as oven-dry, of course, the moisture factors in the above formula drop out, and would not enter into the calculations. In the table, for example, sample 1 has an indicated B. t. u. for the dry coal of 12 356. The calculations, therefore, for each column are

$$(a) = \frac{12356}{1.00 - .1166} = \dots\dots\dots 13\,987$$

$$(b) = \frac{12356 - 4050 (.0599)}{1.00 - (.1166 + .0599)} = \dots\dots\dots 14\,709$$

$$(c) = \frac{12356}{1.00 - (.1166 + .0299)} = \dots\dots\dots 14\,477$$

$$(d) = \frac{12356 - 5000 (.0599)}{1.00 - [1.08(.1166) + .02995 + .00299]} = \dots\dots\dots 14\,331$$

From an examination of this table it seems evident that the values in columns (a), (b), and (c) vary for each pair of samples more widely than we should expect, provided our calculation in these cases is based upon the actual coal; the variation, for example, reaching nearly 2 1/2 per cent in No. 9. That a hydration component is the disturbing factor seems evident from the wide variation in the ash of the two divisions of this sample (22.17 per cent to 4.22 per cent), while the sulphur values are sufficiently close to eliminate any variable due to that element. In column (d), however, it is to be noted that the introduction of an amount of hydration equal to 8 per cent of the pyrite-free ash brings the two heat values to a variation of only 41 B. t. u. or less than 1/3 of 1 per cent. The component calling for this correction, therefore, seems to be directly associated with the ash, since the variation

in sulphur is too small to enter into the account. Equally striking evidence of the presence of such a component is seen in the samples numbered 7, 10, 11, and 12. Sample 8 is essentially the same as 7, and while there is not so close an agreement in this sample, still it must be recognized as confirmatory of the general proposition. If, for example, we admit a manipulation variant of 40 or 50 units, it is hardly to be expected that the other variables, such as the true amount of hydration or the exact character of the same, whether hydration of shale or carbonating of lime, may not carry with it an equal variable, so that in the present stage of our knowledge, it seems fair to consider even this variation quite within reasonable limits.

Another phase of these results is also to be noted. The agreement as to results just given above is seen to depend in large measure upon the correction of the high ashes in those samples referred to, by addition of a component which we have designated as hydration. Fortunately, the list of samples also includes coals high in sulphur, and this affords the necessary condition to show whether or not the sulphur enters into the proposition as a variable, and also what method of correction will most nearly neutralize its effect. Here, again, the close agreement, as in samples 1, 2, 4, 5, and 6, indicates that the method employed is correct in principle; that is, the heat value of the sulphur, taken as 5000 times the sulphur content, is subtracted from the indicated heat units, and the ash is restored as nearly as is conveniently possible, to include the sulphur as joined to the iron in its original or pyritic form. It is realized, as already indicated, that an error is inherent in this procedure, if that part of the sulphur is present as organically combined. Strictly considered, therefore, it should not be reckoned as pyritic sulphur. Test has been made, however, of introducing a further refinement into the calculation by separating the sulphur into the organic part and the inorganic, the amount of the latter being indicated by the content of iron present in the ash. The iron pyrites thus calculated, Table 2, on this iron basis has been

made a part of the original non-coal substance. The 8 per cent of hydration, etc., has then been calculated to the ash as corrected for this amount of pyrites burned to oxide, and finally the organic sulphur has been added as a part of the non-coal matter. The indicated heat units were diminished by the total heat to be credited to the sulphur, taking account of its two forms as indicated in the formula for column (e), thus

(e) =

$$\frac{\text{B. t. u.} - [5247 \times 8/7 \text{ Fe} + 4050 \times (\text{S} - 8/7 \text{ Fe})]}{1.00 - [\text{Moisture} + \text{Ash} + 5/7 \text{ Fe} + .08 (\text{Ash} - 10/7 \text{ Fe}) + (\text{S} - 7/8 \text{ Fe})]}$$

In this formula, the iron weighed as Fe_2O_3 has a ratio of oxygen to iron of 48 : 112 or 3/7. To restore it to an equivalent of FeS_2 which has a ratio of S (64) to Fe (56) or 8 : 7 would require the addition to the ash content of 5/7 of the iron as determined. Similarly 8/7 of the iron value represents the sulphur as originally joined to the iron in the pyritic form, and 10/7 of the iron represents the Fe_2O_3 as a component part of the ash as weighed.

Since the analytical values refer to the coal on the dry basis, the factor for moisture drops out of the formula. The results of this method of calculating are given for the first six samples in column (e) of Table 2, placed in comparison with column (d) repeated from the previous table. As may be readily seen, the relative values are in substantially the same agreement as before. This method involves the added requirement of an iron determination and does not altogether remove the uncertainty as to the form in which the combinations of sulphur occur. In the present state of our knowledge, as well as on the score of practicability, we seem to be justified in accepting the values and formula as given in column (d).

The arguments thus far brought forward to prove the correctness of the method for arriving at the real weight of non-coal substance are sufficiently conclusive for the twelve samples included in the table. How generally applicable this method will be for all types and all regions, remains for the subsequent part of this paper to discuss.

TABLE 2

COMPARATIVE VALUES OF "ACTUAL COAL"

Tab. No.	Lab. No.	DESCRIPTION OF SAMPLE	OVEN-DRY COAL				(d)	(e)
			Ash	Sul- phur	Iron	B. t. u.		
1	6130	Sangamon Co., Ill., Lump Coal: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	11.66	5.99	3.38	12356	Diff. 14331 14340 + 9	Non-coal as Ash, Water, Pyritic Sulphur, Organic Sulphur, and 8% Ash as Corrected for Actual Fe ₂ O ₃ 14494 14536
2	6131		6.12	3.20	.65	13300		
3	6122	Sangamon Co., Ill., Screenings: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	18.21	4.25	2.37	11478	-50	14569 14567 - 2
4	6123		8.13	2.95	.70	13043		
5	6290	Williamson Co., Ill., Washed Nut: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	12.83	1.85	1.09	12523	- 1	14605 14659 + 54
6	6121		4.01	1.39	.54	13929		
7	6129	LaSalle Co., Ill., Washed Screenings: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	10.05	3.43	2.32	12885	+49	14620 14680 + 60
8	6128		3.94	2.33	1.29	13922		
9	6132	Vigo Co., Ind., Nut: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	16.84	7.62	5.17	11790	-60	14779 14783 + 4
10	6133		4.27	3.08	1.06	13870		
11	6135	Sullivan Co., Ind., Lump: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	6.11	3.37-	2.24	13664	-41	14833 14770 - 63
12	6134		2.53	1.29	.36	14259		

As a possible source of variation, the different layers of the same seam were studied with a view to determining inherent variations in the stratification of the coal, which, by variations in sampling or mining, might enter into the case and to a certain extent, modify the fact of uniformity. Three mines were, therefore, sampled with reference to the top, middle, and bottom layers of coal, or with reference to certain zones or bands of coal that seemed to have a structure more or less characteristic and distinct from the other layers. These results are listed in the following table, the basis of comparison being the thermal units calculated to "unit coal," which in subsequent discussion, as already indicated, will be the term made use of in this paper for that coal free from ash, moisture, pyrites, and volatile inorganic matter, as calculated under column (*d*) in Tables 1 and 2.

Attention is called to the following points. In the Collinsville sample, the bands of division were approximately the upper 2 feet, the lower 2 feet, and the middle zone of about 4 feet. When referred to the "unit coal" basis, the upper and middle divisions are in close agreement. The lower layer is considerably higher. This fact would have a modifying influence on the entire face of the seam as is illustrated in No. 4, which is a calculated composite value based on the factors for samples No. 1, 2 and 3. No. 5 and 6 are samples taken from the entire face of the seam, and taken from a mine located not over 2 or 3 miles from the mine from which the first samples by layers were taken. It is evident that the values indicated for the separate layers are not variable to an extent which would noticeably change the ultimate value for the entire face. Moreover, in the process of mining, the output represents the face of the vein and not the various layers. However, the facts brought out in this comparison of the various strata are valuable as indicating certain variations in composition of the same seam which might result from changes in the relative thickness of certain bands. In the same region, or in the same vein, these possible variations due to this phase of the matter would seem to be practically negligible when we consider

the regular output of the mine, since a mixture of the entire seam is inevitable, and these small variations of the layers would be very easily neutralized.

The same statement is applicable to the results as shown for the two additional sections similarly examined from Belleville

TABLE 3

VARIATIONS IN THE CALORIFIC VALUE OF THE "UNIT COAL" FOR DIFFERENT HORIZONTAL LAYERS OF THE SEAM

Tab. No.	Lab. No.	DESCRIPTION OF SAMPLE	OVEN-DRY COAL			Non-coal as 1.08 Ash + 22/40 S. Ref. to B. t. u. — 5000S.
			Ash	Sul-phur	B. t. u.	
		COLLINSVILLE, ILLINOIS				
1	725c	Top 23 in.....	6.14	4.44	13505	14606
2	725b	Middle 48 in.....	12.02	3.84	12618	14634
3	725a	Bottom 22 in.....	14.86	7.52	12297	14936
4	725	Calculated for entire face 93 in.....	11.22	4.85	12762	14694
5	723	Sample taken from entire face.	12.23	4.37	12604	14675
6	724	Sample taken from entire face.	9.69	3.33	12982	14613
		BELLEVILLE, ILLINOIS				
1	1000	Top 4 in.....	6.75	3.35	13629	14814
2	999	$\frac{1}{4}$ in.; 2 in. from the top.....	2.09	2.66	14255	14667
3	995	Entire face, 76— $\frac{1}{2}$ in.....	12.47	4.19	12587	14694
		DUQUOIN, ILLINOIS				
1	422	Top 30 in.....	6.13	.76	13573	14560
2	421	Bottom 69 in.....	14.71	.98	12181	14516
3	.....	Entire face. 99 in.....	12.11	.91	12603	14531

and Duquoin. The agreement is even more marked than in the case of the Collinsville seam.

Notwithstanding these evidences of uniformity, the fact should not be lost sight of that these results have a special value in that they show at a glance the necessity of care in taking face samples, to see that the cut is made equally and from the entire working face of the seam. It is evident also that lump or hand samples which are frequently taken for analysis are not only of

little value but are as a rule positively misleading, and the error is quite as likely to be of a minus as of a plus character.

IV. ASH COMPOSITION

Notwithstanding the very satisfactory indication of the adaptability of the proposed formula for arriving at the unit coal values, as shown by the foregoing Tables 1 and 2, the question still remains as to whether the samples chosen are sufficiently typical to represent all the varieties of composition so far as the ash or inorganic content is concerned. Under this division of the subject, therefore, is taken up a study of this phase of the matter. As a first step, it was deemed necessary to make an analysis of the ash of the coals selected for use in the above tables. For example, the somewhat arbitrary factor, 8 per cent, has been adopted as covering a constant amount of volatile inorganic constituent to be reckoned with the total ash. It may make an appreciable difference whether this component is present as water of hydration, as in a clay or shale, or combined with lime as carbon dioxide. If in the latter combination, the amount of lime present would be an indication of that fact, while the amount of alumina present might serve to indicate the likelihood of this percentage being represented by hydration of shale or clay. An analysis of the ash of the 12 samples as listed in Table 2 is given in Table 4.

In this table, attention is first called to the fact that, with the exception of sample 3, the amount of lime is quite uniform. Here the lime approximates 12 per cent. By reference to the column for alumina, which might be taken as an indication of the clayey matter present, a very fair uniformity also exists, with the possible exception of sample 11, where the aluminium content is relatively low. Now, turning to Table 2 for an indication of a variation in the calculated values for unit coal, it does not seem that these variations in samples No. 3 and No. 11 have entered into the case in an appreciable degree.

Thus far it might be safe to conclude, that the adoption of

the 8 per cent constant, as representing the volatile matter of the ash, is applicable. However, if in this group we have a variation in the lime content from 2 to 12 per cent, as in samples 7 and 3, have we any evidence that it stops there? Similarly,

TABLE 4
ASH COMPOSITION OF COALS OF TABLE 2

Tab. No.	Lab. No.	DESCRIPTION	Ash in Dry Coal %	ANALYSIS OF ASH Per Cent				
				SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
1	6130	Sangamon Co., Ill., Lump.	11.66	33.1	42.5	17.9	5.6	0.9
2	6131	Sangamon Co., Ill., Lump.	6.12	54.2	16.4	24.2	4.1	1.2
3	6122	Sangamon Co., Ill., Screenings.....	18.21	49.2	20.7	17.1	11.9	1.1
4	6123	Sangamon Co., Ill., Screenings.....	8.13	55.9	13.0	23.6	6.7	0.8
5	6290	Williamson Co., Ill., Washed Nut.....	12.83	54.1	12.1	23.8	6.7	1.2
6	6121	Williamson Co., Ill., Washed Nut.....	4.01	51.7	19.3	24.6	2.4	1.0
7	6129	La Salle Co., Ill., Washed Screenings.....	10.05	40.3	34.0	22.8	2.0	0.9
8	6128	La Salle Co., Ill., Washed Screenings.....	3.94	.....	.....	.....	.....	.....
9	6132	Vigo Co., Ind., Nut.....	16.84	32.9	43.8	20.5	2.9	0.9
10	6133	Vigo Co., Ind., Nut.....	4.27	35.1	35.6	25.3	2.3	0.6
11	6135	Sullivan Co., Ind., Lump..	6.11	27.1	52.3	14.1	4.4	1.2
12	6134	Sullivan Co., Ind., Lump..	2.53	45.8	20.2	28.3	5.4	0.0

if the alumina may drop from 25 per cent (No. 10) to 14 per cent (No. 11), can we conclude that these numbers represent the limits of variation, and, if not, will greater variations in these factors cause a disturbance in the factor chosen to represent the volatile matter present?

In extending our study over a wider range of ash analysis, we soon come upon cases where much higher percentages of lime are in evidence. In view of this fact, it was considered worth while to estimate also the carbon dioxide and the chlorine. The carbon dioxide would be a more direct index of volatile loss of ash than the content of lime, since the latter might be combined in other than carbonate form. Chlorine, if present in any form,

would be volatile, depending on the temperature made use of. Table 5 is given as illustrating the extremes to which lime as calcium carbonate, and alumina combined as clayey matter may be met, at least in the ash from Illinois coals.

TABLE 5
ASH COMPOSITION OF COALS WITH HIGH PERCENTAGE OF LIME

Tab. No.	Lab. No.	DESCRIPTION	In per cent of Dry Coal			ANALYSIS OF ASH				
			Ash	CO ₂	Cl	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
1	734	Grundy Co., Ill.....	5.82	.88	none	22.8	32.4	10.2	34.0	0.7
2	1095	Saline Co., Ill.	11.49	1.22	.04	32.7	33.0	9.0	25.3	0.8
3	1178	Clinton Co., Ill.....	15.56	2.48	.10	39.0	22.4	6.3	31.7	0.7
4	1403	Peoria Co., Ill.....	15.46	2.48	none	25.7	12.9	6.8	54.5	1.5

It might be argued from the results in Table 5, that whereas the lime content is high, the alumina is low, and there is, therefore, a compensation which would still furnish evidence that the 8 per cent constant for the inorganic volatile matter would be applicable. However, to test the matter, it was deemed advisable to subject these samples to the floating test as already indicated, giving as a result two divisions of each sample; one with an abnormally low ash, the other with an abnormally high ash; the latter division in each case still further accentuating the lime factor. In consequence of this division, the analysis of the eight resulting samples together with the calorific values is presented in Table 6. Columns (a) and (d) only are given in order that a comparison may be made between the ash values for "ash and water-free" or "pure coal" with the "unit coal" values as derived by the formula already made use of on page 14.

From the calculations under column (a) and column (d), it is evident that the wide discrepancies under column (a) are due to a failure to take into consideration those mineral constit-

units of the coal which properly belong to the ash. This is the fuel unit designated the "ash and water-free," combustible or "pure coal" basis adopted by engineers. Under column (d), the

TABLE 6

PROXIMATE ANALYSIS WITH CALORIFIC VALUES FOR FLOAT AND SINK COAL WITH HIGH PERCENTAGES OF LIME IN THE ASH

Tab. No.	Lab. No.	DESCRIPTION	In per cent of Dry Coal			Heat Value of "Actual Coal" as Calculated by Different Methods	
						(a)	(d)
			Ash	Sul.	B. t. u.	"Pure Coal" Basis	"Unit Coal" Basis
						B. t. u. 1.00 - Ash	B. t. u. - 5000S. 1.00 - (1.08 Ash + $\frac{22}{40}$ S.)
1	734	Float, Grundy Co.	4.57	1.44	13475	14120	Diff.
2	734	Sink, Grundy Co.	21.99	5.00	10733	13760	14217
3	1095	Float, Saline Co.	6.42	2.65	13663	14600	14262
4	1095	Sink, Saline Co.	19.94	7.01	11122	13902	+ 45
5	1178	Float, Clinton Co.	8.54	1.96	12634	-698	14768
6	1178	Sink, Clinton Co.	31.90	3.75	8856	13813	14906
7	1403	Float, Peoria Co.	10.37	2.39	12796	13004	+138
8	1403	Sink, Peoria Co.	34.24	4.71	9216	-809	13975
						14276	13654
						14014	-321
						-262	14489
							14859
							+370

unit coal values come very much closer together, but are not in such satisfactory agreement as was the case with the coals in Table 2, having a low lime content in the ash. It is evident, therefore, that in these two extreme divisions which have been made by the process of floating out to get the lighter and sinking the heavier ash coal, the inorganic volatile matter must be accounted for in some further correction than would be included in the 8 per cent adopted in calculation for Table 2. It is evident in this set of samples, that we have accentuated in an extreme manner the effect of a high ratio of carbonate of lime, bringing this constituent up to 16.67 per cent of the total coal in No. 5 of

the table, and to 11.99 per cent in No. 6. While these percentages are abnormal, they serve well the purpose of indicating the effect upon the proposed formula for arriving at unit coal values. The first question which presents itself, therefore, is whether we should not correct our ash factor, not by an 8 per cent addition alone, but by adding directly to the ash as weighed, the amount of carbon dioxide present, on the assumption that all of the calcium carbonate would be decomposed, setting free the CO_2 . This involves another hypothesis, namely, that in the ordinary determination of ash, the calcium carbonate present is completely decomposed. To test this point, the four samples, subdivided into pairs of low and high ash each, were subjected first to the ordinary ash determination as directed by the Committee of the American Chemical Society on standard methods for coal analysis. No important modification of this method was employed. After complete burning off of the carbon in a porcelain crucible over a Bunsen lamp, a blast lamp, driven at moderate intensity, was applied for 30 to 40 minutes. The results are listed in Table 7, in the first column for ash percentages, marked (*a*). In the column marked (*b*), the method employed made use of a platinum crucible and after burning off the carbon, an intense heat was applied by means of the blast lamp, continuing the blasting to constant weight. As will be seen from these results, a very wide difference may be made in the seemingly simple matter of determining the ash. Evidently under column (*a*) only a part of the calcium carbonate has been decomposed in the "sink" samples.

In this table, therefore, we have a striking illustration of the variations that may enter into the ash determination. The evidence of a variable element indicated its presence in a very marked manner in the process of obtaining the values for column (*a*). It was found almost impossible to secure duplicate results, the values sometimes varying in the two portions run in parallel by as much as 1.00 per cent. This evidence of a high content of calcium carbonate and its effect on the accuracy of the ash deter-

TABLE 7

VARIATIONS IN ASH VALUES WHERE CALCIUM CARBONATE IS A CONSTITUENT OF THE COAL

Tab. No.	Lab. No.	DESCRIPTION	(a) Ash as Determined by Usual Method	(b) Ash as Determined by Blasting to Constant Wght and Fusion	Difference in per cent of Dry Coal
1	734	Float, Grundy Co., Ill.	4.57	3.54	1.03
2	734	Sink, Grundy Co., Ill. . .	21.99	16.85	5.14
3	1095	Float, Saline Co., Ill. . .	6.42	5.96	0.46
4	1095	Sink, Saline Co., Ill. . . .	19.94	18.59	1.35
5	1178	Float, Clinton Co., Ill. . .	8.54	7.23	1.31
6	1178	Sink, Clinton Co., Ill. . . .	31.90	26.88	5.02
7	1403	Float, Peoria Co., Ill. . . .	10.37	9.08	1.29
8	1403	Sink, Peoria Co., Ill. . . .	34.24	22.93	11.31

mination is of far-reaching importance. It affects in a very material manner any method of reference to a unit of combustible, especially such as is made use of by the engineering profession under the designation of "ash and moisture-free" material. It also seriously affects those results in a coal analysis which are obtained indirectly by difference. For example, the value for fixed carbon is thus estimated. Any error in the ash determination is therefore loaded upon this constituent. An equally erroneous feature accompanies the ultimate analysis where the total carbon is measured as CO_2 . The carbon dioxide combined with the calcium oxide in the coal is thus made to appear in the final result as augmenting the value for total carbon. But it is not the purpose here to discuss the effect of this possible source of error. The immediate problem in hand is to arrive at the actual non-coal or inorganic substance as an essential factor in calculating the values for unit coal. The obvious suggestion, therefore, would be to make a determination of all possible volatile constituents, especially the CO_2 and Cl and augment the ash values found at the higher temperature by these percentages. Such an analysis was made, as shown in Table 8. A complete

analysis was also made showing all the mineral constituents, so that any bearing these factors might have, could be studied simultaneously with the question of the true ash or inorganic matter.

In considering the probable reactions of the ash at a fusion temperature, it would be conceded at once that all of the CO_2 would be driven off. This, therefore, would be the first increment to add to the ash as above determined. Similarly, the chlorine present would be driven off. Evidently, in these particular samples, the larger portion of the chlorine is combined as CaCl_2 , which was not washed out of the texture of the coal after being subjected to the floating process in a CaCl_2 solution. But whether joined as NaCl or CaCl_2 , it is probable that the ultimate result is the formation of silicates of sodium and calcium with liberation of chlorine. Hence it seems proper to add a second increment to the ash values, that of the chlorine percentages. When we come to a disposition of the SO_3 value, the case is not so clear. Ordinarily, it should be noted, the amount of sulphate present in a coal is so small as to be negligible, but it so happens that the samples selected for this particular series had been in laboratory storage for over a year, with the result, that when the ultimate constituents were all sought out, quite an appreciable amount of sulphate of iron had formed. Now the decomposition of this material is easily effected at a temperature above 300° . Hence the indication would seem to be that a further correction for the ash content should be made by adding the percentage found for this constituent. However, it should be borne in mind that calcium carbonate is present in sufficient quantity to take care of this SO_3 by formation of $\text{CaSO}_4 + \text{CO}_2$. By testing artificial mixtures of calcium carbonate and ferrous sulphate, with and without the addition of organic matter, the residual fusion showed sufficient sulphate remaining as CaSO_4 to warrant the conclusion that no correction should be made for the SO_3 found to be present in the original coal.

In view of these facts, therefore, the calculation for the unit

TABLE 8--Ash Composition--In per cent of dry coal

Tab. No.	Lab. No.	Description	Ash by Blasting to Constant Weight and Fusion in Pt. Cruc.	SiO ₂	Fe ₂ O ₃ Al ₂ O ₃	CaO MgO	Na	Cl	SO ₃	CO ₂	Total S	B. t. u.
1	734	Float.....	3.54	.98	1.71	.85	.12	1.00	.43	.10	1.44	13475
2	734	Sink.....	16.85	2.44	7.91	6.50	.31	1.15	1.05	3.68	5.00	10733
3	1095	Float.....	5.96	2.93	2.63	.40	.07	.17	.22	.13	2.65	13663
4	1095	Sink.....	18.59	5.23	9.48	3.88	...	.31	.81	2.38	7.01	11122
5	1178	Float.....	7.23	3.33	3.02	.88	.23	1.41	.20	.21	1.96	12634
6	1178	Sink.....	26.88	9.03	9.49	8.36	.27	1.20	.56	5.27	3.75	8856
7	1403	Float.....	9.08	5.46	2.33	1.29	.22	1.07	.23	.31	2.39	12796
8	1403	Sink.....	22.93	5.64	7.09	10.20	.19	1.17	.99	7.35	4.71	9216

TABLE 9--"UNIT COAL" IN SAMPLES WITH HIGH CALCIUM CARBONATE

Tab. No.	Lab. No.	Description	IN PER CENT OF DRY COAL				"PURE COAL"		"UNIT COAL"	
			Ash as Determined by High Fusion to Constant Weight	CO ₂	Cl	B. t. u.	B. t. u. — Ash		B. t. u. — 5000S	
							1.00 —		1.00 —	
							(1.08 Ash (corr.) + ²² / ₄₀ S.)		(1.08 Ash (corr.) + ²² / ₄₀ S.)	
							Diff.		Diff.	
1	734	Float.....	3.54	.10	1.00	13475	13969		14219	
2	734	Sink.....	16.85	3.68	1.15	10733	12908		14214	
3	1095	Float.....	5.96	.13	.17	13663	14528		14742	
4	1095	Sink.....	18.59	2.38	.31	11122	13662		14736	
5	1178	Float.....	7.23	.21	1.41	12634	13618		14030	
6	1178	Sink.....	26.88	5.27	1.20	8856	12111		14009	
7	1403	Float.....	9.08	.37	1.07	12796	14073		14508	
8	1403	Sink.....	22.93	7.35	1.17	9216	11941		14172	
							— 1061		— 5	
							— 866		— 6	
							— 1507		— 21	
							— 2132		— 336	

coal values on these samples was based on an ash content in which the ash as weighed had been subjected to a very high temperature in a platinum crucible, and continued until a constant weight was secured, and the ash fused; to this was added the CO_2 present in the dry coal, and also the factor for chlorine. The formula already given, therefore, was simply modified by the above conditions, and would be expressed as follows:

$$\text{Unit Coal} = \frac{\text{Indicated B. t. u.} - 5000 \text{ S}}{1.00 - [(\text{Ash} + \text{CO}_2 + \text{Cl}) \times 1.08 + 22/40 \text{ S}]}$$

The results of this calculation are given in Table 9, with a comparison wherein the values are calculated to "pure coal" or the "ash and water-free" basis and to the "unit coal" with the ash corrected for the CO_2 and Cl present.

Concerning these results, the proposed correction of the ash by addition of the CO_2 and Cl would seem to meet the conditions as indicated by the close agreement of the "unit coal" values. The last sample, No. 8 of the table, is not in so good agreement as could be wished. The only explanation to be suggested at the present time is that the very high per cent of calcium carbonate, 16.67 per cent, would seem to require that a correction be made in the calorimetric value to allow for the heat of decomposition required to separate that amount of calcium carbonate into its constituent parts. This would mean that 786.6×16.67 per cent or 131 B. t. u. would represent the heat of dissociation for the calcium carbonate present. This amount, added to the indicated heat, would represent the total heat developed in the combustion as 9112 B. t. u. This amount introduced into the formula would show 14 383 B. t. u. as the unit coal value, or a difference from the low ash sample of 112 units instead of 336 as in the table. More study of this extreme type of coal must be made, and upon fresh samples with the sulphate constituent eliminated, before a final judgment can be formulated as to the adaptability of the formula to such cases. The remarkable conformity of the values in three of the four cases would seem to

argue strongly in favor of the corrections for CO_2 and Cl as covering the case. In consideration of the facts set forth, therefore, in these last tables, it was deemed necessary to make an extended inspection of the coals of the State with special reference to their content of carbonate and chlorine. About sixty samples were selected and in addition to the usual ash determination, analysis

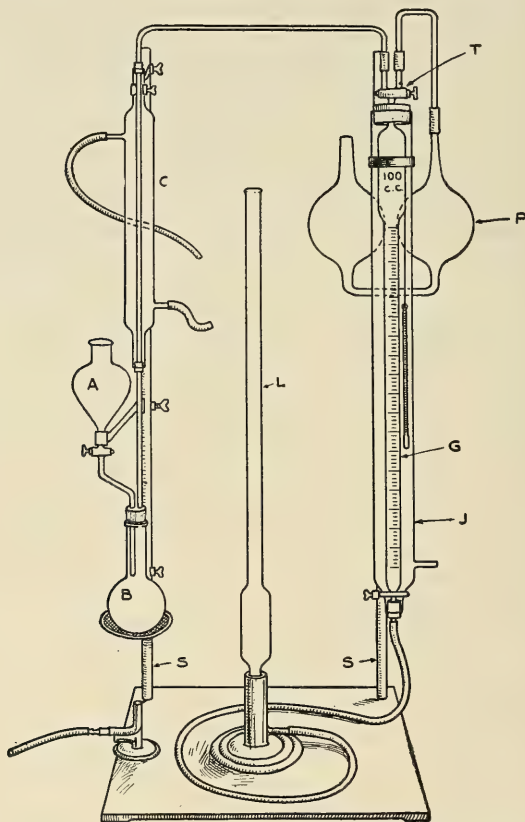


FIG. 1 APPARATUS FOR DETERMINING CO_2

was made of the ash constituent, namely, silicon, iron, alumina, lime, and magnesia. In addition, a determination was made of the chlorine and carbonate present. The chlorine was determined by digesting 2 grams of the pulverized coal on a steam

bath with about 200 cc. of water, filtering, making up to 500 cc., and titrating an aliquot part with standard silver nitrate solution.

The carbonate was determined by weighing out 5 grams of coal and treating with acid in the apparatus designed for such work as shown in Fig. 1. This is an improved form of the apparatus described in Bulletin 7 of the Engineering Experiment Station, for the volumetric estimation of carbon dioxide, by absorbing the same in a pipette, as *P* of the figure, and measuring the contraction in the jacketed burette.

From the values thus obtained for these two constituents, it will be seen from the table that the high amounts of both are distributed quite irregularly throughout the State, and very frequently in a sufficiently high amount to make the introduction of their values into any careful analytical work on such coals an essential feature, if trustworthy results are to be forthcoming.

An answer is thus afforded, in such cases at least, to the query of the Committee of the American Chemical Society on Coal Analysis¹: "Are carbonates likely to be present in the ash in such amount that heating over a blast lamp would lessen the weight appreciably?" An affirmative answer is also indicated in Table 7, where the weight of ash is lessened on blasting by 11.31 per cent of the coal, as in sample 8.

A further suggestion results from these frequent indications of carbon dioxide. The high carbonate content is accompanied by a high lime factor and the question at once occurs as to whether this factor for CO_2 might not serve as an index of fusibility of the ash quite as accurately as the content of sulphur, since high lime is as promotive of slagging as iron. Numerous tests on the fusibility of ash have confirmed this idea. It is hoped that this matter of the fusibility of coal ash may be taken up for further study in the near future.

¹Jour. Am. Chem. Soc. Vol. 20, p. 284, 1898.

TABLE 10

ANALYSIS OF COAL ASH

(Including Values for CO₂ and Cl)

Tab. No.	Lab. No.	DESCRIPTION		Ash and Volatile Inorganic Matter Dry Coal Per Cent		MINERAL CONSTITUENTS OF ASH AS OBTAINED BY HIGH FUSION					
						Per Cent					
		LOCATION	Seam No.	Ash by Usual Method	CO ₂	Cl	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
1	733	S. Wilmington, Grundy Co.....	2	8.17	.15	None	28.8	41.1	22.5	7.0	.6
2	734	Coal City, Grundy Co.....	2	5.82	.88	"	22.8	32.4	10.2	34.0	.7
3	1411	Hollis, Peoria Co.....	2	10.90	.98	.27	33.3	41.8	10.2	16.6	.7
4	896	Spillerton, Williamson Co.....	5	10.68	.70	.31	43.2	37.9	12.5	3.9	.5
5	1092	Equality, Gallatin Co.....	5	10.85	.72	None	39.5	29.6	8.5	23.8	1.0
6	1094	Eldorado, Saline Co.....	5	10.54	.26	.15	42.8	38.3	9.3	8.3	1.3
7	1095	Eldorado, Saline Co.....	5	11.49	1.22	.04	32.7	33.0	9.0	25.3	.8
8	1110	Eldorado, Saline Co.....	5	12.68	.51	.14	30.6	49.7	7.3	13.0	.8
9	1112	Harrisburg, Saline Co.....	5	8.99	.11	None	48.7	26.1	22.5	3.2	1.2
10	1115	Ledford, Saline Co.....	5	11.58	.34	"	40.0	26.4	21.8	9.3	1.1
11	1116	Ledford, Saline Co.....	5	9.89	.05	.05	29.4	20.0	20.3	26.5	2.0
12	540	Springfield, Sangamon Co.....	5	10.76	.32	.08	40.5	37.0	8.2	11.8	.5
13	720	Lincoln, Sangamon Co.....	5	13.81	.54	.32	35.1	22.4	10.2	30.8	1.5
14	740	Springfield, Sangamon Co.....	5	12.75	.34	None	56.4	14.9	18.4	9.1	1.2
15	741	Springfield, Sangamon Co.....	5	12.47	.85	.24	43.3	24.1	9.0	19.9	1.2
16	1403	Bartonville, Peoria Co.....	5	15.46	2.48	None	25.7	12.9	6.8	54.5	1.3
17	1404	Canton, Fulton Co.....	5	12.52	1.30	"	43.9	20.1	12.3	22.4	1.3
18	1407	Edwards Sta., Peoria Co.....	5	16.25	2.15	.03	33.1	30.6	3.2	31.1	.8
19	1410	Maxwell, Peoria Co.....	5	14.78	1.57	None	34.3	24.8	8.1	31.3	.7
20	1412	E. Peoria, Tazewell Co.....	5	.....	.61	.19	45.0	26.3	11.6	16.1	1.0
21	1413	Pekin, Tazewell Co.....	5	.....	1.36	None	43.0	17.7	6.6	31.6	1.0

TABLE 10

ANALYSIS OF COAL ASH

(Including Values for CO₂ and Cl)—(Continued)

Tab. No.	Lab. No.	DESCRIPTION		Ash and Volatile Inorganic Matter Dry Coal Per Cent				MINERAL CONSTITUENTS OF ASH AS OBTAINED BY HIGH FUSION Per Cent				
				Ash by Usual Method	CO ₂	Cl		SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
		LOCATION		Seam No.								
22	557	Westville, Vermilion Co.		6	1.08	.15		47.9	26.9	18.5	5.6	1.1
23	558	Westville, Vermilion Co.		6	8.03	.15		52.9	23.8	5.8	17.1	.3
24	722	Thayer, Sangamon Co.		6	11.04	.19		44.0	32.0	13.2	9.8	1.0
25	725a	Collinsville, St. Clair Co.		6	11.22	.70	None	50.9	17.3	19.5	11.8	.6
26	725b	Collinsville, St. Clair Co.		6	.....	.72	"	48.2	18.2	21.3	11.0	.3
27	725c	Collinsville, St. Clair Co.		6	.....	.37	"	33.6	27.2	11.4	16.8	1.2
28	735	Mt. Olive, Macoupin Co.		6	10.86	.36	.16	40.7	32.5	17.0	9.8	.8
29	736	Mt. Olive, Macoupin Co.		6	11.40	.13	.22	49.1	32.2	13.5	4.5	1.4
30	991	Belleville, St. Clair Co.		6	15.80	.....	.....	44.8	20.3	18.6	16.4	1.5
31	996	Germantown, Clinton Co.		6	10.47	.44	.23	38.8	27.5	19.4	13.2	1.1
32	1001	Lebanon, St. Clair Co.		6	12.53	.65	.12	52.9	16.7	17.3	11.8	1.3
33	1002	O'Fallon, St. Clair Co.		6	13.43	.50	.16	44.3	28.4	13.2	11.5	1.3
34	1003	S. W. of O'Fallon, St. Clair Co.		6	12.94	.76	None	44.4	19.3	20.8	16.1	1.1
35	1117	Donkville, Madison Co.		6	10.59	.64	None	40.8	27.4	13.2	16.9	1.6
36	1118	Troy, Madison Co.		6	13.65	.55	.05	44.8	19.2	21.2	11.2	1.1
37	1119	Maryville, Madison Co.		6	11.72	.71	.09	45.6	27.0	5.8	20.8	.8
38	1176	Breese, Clinton Co.		6	13.59	.40	.33	55.5	21.4	5.9	16.4	.8
39	1178	Trenton, Clinton Co.		6	15.56	2.48	.10	39.0	22.4	6.3	31.7	.7
40	419	Zeigler, Franklin Co.		7	10.11	.37	.50	59.0	3.1	31.0	5.6	1.3
41	420	Zeigler, Franklin Co.		7	7.53	.21	.55	54.3	9.0	29.1	6.3	1.3
42	421	DuQuoin, Perry Co.		7	14.71	.65	.42	55.2	8.3	26.6	7.3	1.3

TABLE 10

ANALYSIS OF COAL ASH
(Including Values for CO₂ and Cl)—(Concluded)

Tab. No.	Lab. No.	DESCRIPTION LOCATION	Ash and Volatile Inorganic Matter DRY COAL Per Cent		MINERAL CONSTITUENTS OF ASH AS OBTAINED BY HIGH FUSION Per Cent					
			Ash by Usual Method	CO ₂	Cl	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
43	422	DuQuoin, Perry Co.....	.....	.28	.47	53.9	7.8	28.0	6.7	1.0
44	459	Herrin, Williamson Co.....	8.48	.12	.13	59.9	8.1	29.4	1.9	1.0
45	460	Herrin, Williamson Co.....	10.13	.47	.12	56.1	8.1	27.2	5.4	.9
46	461	Sesser, Franklin Co.....	.....	.28	.56	51.4	10.2	31.5	5.7	1.1
47	462	Marion, Williamson Co.....	7.66	.14	None	50.1	20.0	26.2	2.9	.8
48	1088	Herrin, Williamson Co.....	10.65	.35	..	46.2	31.5	9.0	12.8	.6
49	1120	Galatia, Saline Co.....	.....	1.20	.07	45.4	25.3	16.9	11.6	.8
50	1121	Norris City, White Co.....	11.50	.41	.20	41.4	34.6	10.6	12.1	1.2
51	....	Taylorville, Scrgs. Comp.....	.....	.....	.....	45.1	21.5	19.8	12.4	1.0
52	6121	Marion, W. Nut.....	.....	.....	.....	51.7	19.3	24.6	2.4	1.1
53	6122	Lincoln, scrgs.....	.....	.....	.....	49.2	20.7	17.1	11.9	.8
54	6123	Lincoln, scrgs.....	.....	.....	.....	55.9	13.0	23.6	6.7	.9
55	6129	La Salle, W. scrgs.....	.....	.....	.....	40.3	34.0	22.8	2.0	.9
56	6130	Pawnee, Lump.....	.....	.....	.....	33.1	42.5	17.9	5.6	.9
57	6131	Pawnee, Lump.....	.....	.....	.....	54.2	16.4	24.2	4.1	1.2
58	6132	Vigo County, Indiana.....	.....	.....	.....	32.9	43.8	20.5	2.9	.9
59	6133	Vigo County, Indiana.....	.....	.....	.....	35.1	35.6	25.3	2.3	.8
60	6134	Sullivan Co., Indiana.....	.....	.....	.....	45.8	20.2	28.3	5.4	.0
61	6135	Sullivan Co., Indiana.....	.....	.....	.....	27.1	52.3	14.1	4.4	1.2
62	6290	Marion, Williamson Co., Ill.....	.....	.....	.....	54.1	12.1	23.8	6.7	1.2

V. SUMMARY

The principles developed by the foregoing discussion may be stated as follows:

1. Ordinarily the total inorganic or non-coal constituent is expressed by the formula

$$\text{Total Inorganic Matter} = M + 1.08 A + 22/40 S$$

in which M = moisture, A = ash, and S = sulphur. The formula for calculating the heat value for unit coal, therefore, basing the calculation upon wet coal values, would be

$$\text{B. t. u. of Unit Coal} = \frac{\text{Indicated (wet) B. t. u.} - 5000 S}{1.00 - (M + 1.08 A + 22/40 S)}$$

and for dry coal:

$$\text{B. t. u. of Unit Coal} = \frac{\text{Indicated (dry) B. t. u.} - 5000 S}{1.00 - (1.08 A + 22/40 S)}$$

2. A coal of unknown character as to its carbonate content should be subjected to a carbonate determination readily effected by liberating the CO_2 with acid and measuring the same by weight or volume. Where carbonates are found to exist in any considerable quantity, say over 0.3 per cent CO_2 , the ash determination should be made by blasting in a platinum crucible to constant weight, and the ash as thus determined corrected by adding the weight found for CO_2 . Further, since this method of driving the weight of ash will drive off the chlorine present, this constituent should also be determined and the amount as Cl added to the weight of ash.

It has been possible to apply the foregoing principles to a large number of analyses which have been made in this laboratory. Some from the same mine extending over a considerable period of time afford a good opportunity of verifying the constancy of the unit coal values from the same mine. Others from the same geological seam, extending over a considerable area, as well as those from neighboring mines, serve to demonstrate a positive relationship and, so far as they are available, establish the unit values for their respective regions. An extension of these data has been prepared and arranged in tables following

this discussion. In addition to the results obtained in our own laboratory, the various coal values as published by the Ohio State Survey¹ (Appendix A) and the United States Geological Survey² (Appendix B) have been calculated to unit values by the formula already developed and indicated at the head of the column for "Unit Coal." A most interesting study is there made possible of the constancy of values for a given type of coal or for a given region.

The application which the facts of the tables may be made to serve are many and of far-reaching importance. The real value and the extent of this service hinge upon the accuracy with which we may differentiate between the actual or unit coal and the true ash content. It is believed that the methods and formulas herein proposed are accurate within the limits of variation, inherent in the composition of the unit substance itself, and in the manipulation and methods of analysis employed. Concerning this latter point, it is obviously impossible in applying the calculations to analytical values already published, to take account of errors in ash determination, due for example to the presence of carbonate of lime. Some of the discrepancies in unit values, therefore, may be due to this fact. Moreover, some of the samples grouped by counties may be from different seams and hence show a difference in their unit values. It has not been practicable to give more detail of location or deposit than is contained in the tables, but the facts thus presented seem to have sufficient value to warrant their publication in this form.

An inspection of Table 10, (p. 31), shows a number of coals with over 2 per cent of CO_2 present. This represents approximately 5 per cent of calcium carbonate. In the Mahler type of calorimeter, this material is decomposed, representing a loss of heat amounting to about 40 B. t. u. for each 5 per cent of calcium carbonate present. A question is therefore raised as to the desirability of correcting heat values obtained by that instrument, to take account of this reaction in the calorimeter.

¹Geological Survey of Ohio, Fourth Series, Bul. No. 9, 1908.

²United States Geological Survey, Bulletins No. 261, No. 290, and No. 332.

VI. CONCLUSIONS

1. The actual or unit coal of a given deposit or region is remarkably uniform in composition, as shown by the constancy of heat values, when calculated to such unit substance.

2. The true percentage content of the actual or unit coal hinges upon the correct determination of the inorganic constituents of the coal. The present methods of analysis fail to take account of such constituents as the hydration of the shaley or clayey portions of the ash or the carbon dioxide content of earthy carbonates. The presence of chlorine compounds may sometimes be sufficient in amount to require consideration and estimation.

3. Coal with an ash of unknown composition should be examined for carbonates and chlorides. If the combined amount of these constituents approximates 0.5 per cent, the ash determination should be made at a temperature sufficiently high for their complete elimination, and a correction made for the ash value thus obtained by adding the amount of CO_2 and Cl found.

4. Apart from the corrections which may be called for on account of the presence of CO_2 or Cl, a factor for hydration is necessary, amounting to 8 per cent of the ash as determined, minus the ferric oxide resulting from the decomposition of the iron pyrites.

5. The assembling of the corrections indicated may be embodied in a simple formula, easy of application, and under two headings as follows:

For coals free from carbonates and chlorides

$$\text{Unit B. t. u.} = \frac{\text{Indicated Dry B. t. u.} - 5000 \text{ S}}{1.00 - (1.08 \text{ Ash} + 22/40 \text{ S})}$$

For coals with carbonates and chlorides

$$\text{Unit B. t. u.} = \frac{\text{Indicated Dry B. t. u.} - 5000 \text{ S}}{1.00 - [(\text{Ash at high temp.} + \text{CO}_2 + \text{Cl}) 1.08 + 22/40 \text{ S.}]}$$

VII. TABULATION OF CALCULATED VALUES FOR UNIT COAL

From the tables following, (Tables 11 to 19 inclusive), not only is there evidence of a constancy of values for a given area, but, conversely, a given type of fuel over widely separated areas has a value which varies between relatively narrow limits and may be made to serve as an index of the kind or type and probably the region from which the material comes. From an inspection of these and other data a tentative series of values defining the suggested limits for the generally recognized fuel types is given in Table 11.

TABLE 11

CLASSIFICATION OF FUEL TYPES BY HEAT VALUES FOR UNIT OR ACTUAL ORGANIC SUBSTANCE

Cellulose and wood.....	6500 to 7800
Peat.....	7800 to 11500
Lignite-brown.....	11500 to 12500
Lignite-black.....	12500 to 13500
Sub-bituminous Coal.....	13500 to 14200
Bituminous Coal (mid continental field).....	14200 to 15000
Bituminous Coal (eastern field).....	15000 to 16000
Semi-anthracite and Semi-bituminous.....	15500 to 16000
Anthracite.....	15000 to 15500

TABLE 12
COAL RESULTS

From Continuous Deliveries, September 1, 1907 to September 1, 1908.

Each Sample Represents 5 Cars or 250 Tons, and is a Composite of 5 Separate Samples.

Shipments all from the Same Mine, Christian Co., Ill.

Lab. No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
	Moisture	Ash	Sulphur	B. t. u.	B. t. u. — 5000 S	
					1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
933	13.16	17.07	4.39	9665	14313	-160
934	10.89	17.34	4.87	10104	14564	+ 91
935	13.49	15.14	3.99	10082	14539	+ 66
936	13.76	16.26	4.01	9845	14507	+ 34
937	14.00	16.97	4.41	9680	14499	+ 26
938	12.55	17.40	4.19	9883	14576	+103
939	12.57	18.70	4.43	9709	14643	+170
940	12.99	16.25	4.10	9971	14533	+ 60
941	12.71	17.27	4.55	9871	14580	+107
942	12.18	18.53	5.35	9724	14577	+104
943	11.52	16.13	4.36	10211	14554	+ 81
944	12.21	15.31	4.32	10278	14608	+135
945	13.53	16.14	4.38	9824	14420	- 53
946	14.99	14.96	4.15	9885	14537	+ 64
947	15.07	15.09	4.27	9825	14501	+ 28
948	14.25	15.51	3.91	9896	14510	+ 37
949	12.98	15.25	3.70	10076	14437	- 36
957	13.17	16.40	4.16	9880	14472	- 1
990	13.03	18.05	4.39	9773	14683	+210
1024	14.59	16.20	4.18	9830	14664	+191
1025	13.38	17.51	4.19	9747	14580	+107
1026	14.28	16.31	4.71	9840	14558	+185
1027	13.84	16.56	4.23	9842	14602	+129
1071	13.88	16.06	4.51	9868	14543	+ 70
1072	13.66	16.31	4.46	9837	14505	+ 32
1073	12.99	15.71	4.15	10076	14563	+ 90
1074	12.43	17.95	4.66	9834	14631	+158
1075	12.70	17.01	4.12	9857	14478	- 5
1076	13.79	18.63	4.95	9497	14595	+122
1077	13.62	15.90	4.36	9935	14544	+ 71
1180	13.45	16.68	4.00	9801	14472	- 1
1181	13.17	17.95	4.85	9607	14457	- 16
1182	13.49	13.36	3.97	9964	14415	- 58
1183	12.16	19.20	5.01	9556	14462	- 11
1184	11.90	17.16	4.55	9925	14458	- 15
1185	12.97	16.63	4.60	9893	14522	+ 49
1186	13.73	16.66	4.34	9795	14536	+ 63
1187	13.80	16.10	4.27	9884	14550	+ 77
1188	14.28	15.84	4.54	9763	14424	- 49
1204	14.51	18.04	4.35	9464	14533	+ 60

TABLE 12
COAL RESULTS—(Concluded)

Lab. No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
	Moisture	Ash	Sulphur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
1205	14.13	16.31	4.85	9746	14488	+ 15
1272	15.81	15.18	3.86	9650	14399	— 74
1273	15.21	14.45	4.04	9910	14498	+ 25
1274	15.40	16.08	5.03	9560	14440	— 33
1275	14.04	16.44	4.52	9694	14409	— 64
1276	14.35	18.13	4.62	9315	14299	—174
1326	14.81	16.56	4.22	9540	14354	—119
1327	13.46	17.87	4.65	9505	14335	—138
1328	13.56	17.53	4.67	9568	14373	—100
1329	14.98	14.37	3.90	9928	14451	— 22
1330	14.59	16.63	4.34	9614	14444	— 29
1331	14.10	17.42	4.82	9592	14511	+ 38
1332	13.13	16.12	4.58	9783	14272	—201
1447	13.28	17.10	4.19	9670	14346	—127
1448	12.62	18.18	4.46	9590	14344	—129
1449	13.31	18.15	4.50	9584	14485	+ 12
1450	13.21	16.16	4.21	9852	14385	— 88
1451	13.32	17.01	4.28	9656	14313	—160
1695	15.31	13.19	3.61	9999	14341	—132
1696	16.12	13.10	3.76	9890	14339	—134
1697	15.62	14.29	3.61	9782	14338	—135
1759	14.02	15.62	4.43	9817	14392	— 81
1760	13.83	16.54	4.49	9676	14354	—119
1789	13.49	19.41	4.07	9331	14416	— 57
1832	14.09	17.22	4.17	9605	14451	— 22
1833	13.56	17.07	3.93	9704	14439	— 34
1834	13.56	17.50	4.24	9590	14381	— 92
Av....	13.65	16.58	4.35	9779	14475	± 82

TABLE 13

COAL RESULTS

From Continuous Deliveries September 1, 1908, to May 1, 1909

Each Sample represents 300 Tons

Shipments all from the Same Mine, Vermilion Co., Ill.

Lab. No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
	Moisture	Ash	Sulphur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
1879	12.92	16.58	3.82	9992	14613	-143
1880	14.22	18.16	4.51	9540	14624	-132
1881	12.45	17.22	4.14	9950	14608	-148
1883	13.00	19.48	4.31	9501	14601	-155
1896	12.08	17.13	3.67	10160	14801	+ 45
1897	12.67	16.90	4.26	10062	14757	+ 1
1898	12.71	16.79	4.22	10071	14752	- 4
1899	12.36	18.80	5.17	9801	14794	+ 38
1900	12.36	16.53	5.07	10170	14800	+ 44
1902	12.70	15.20	3.89	10269	14655	-101
1903	12.65	15.27	3.78	10208	14567	-189
1905	12.38	18.00	4.59	9913	14747	- 9
1906	12.46	18.30	4.21	9787	14629	-127
1908	11.76	16.12	3.48	10402	14840	+ 84
1909	11.74	15.10	3.93	10440	14677	- 79
1911	12.34	16.19	4.23	10324	14903	+147
1912	12.59	18.25	4.10	9772	14620	-136
1919	16.76	16.68	3.70	9512	14760	+ 4
1920	16.92	18.20	3.83	9232	14745	- 11
1934	12.93	16.44	3.54	10200	14878	+122
1942	12.72	17.62	4.07	9949	14763	+ 7
1943	15.03	16.45	4.09	9846	14844	+ 88
1947	13.90	18.31	4.08	9689	14800	+ 44
1990	14.47	15.57	3.85	10021	14759	+ 3
1991	13.31	18.08	4.35	10020	15134	+378*
1987	12.80	14.51	3.64	10476	14805	+ 49
1988	12.68	14.54	3.80	10508	14840	+ 84
1993	13.19	17.33	4.16	9931	14777	+ 21
1994	13.31	18.44	4.15	9849	14947	+191
1996	11.85	20.36	5.47	9720	14958	+202
1997	12.05	20.83	4.13	9512	14728	- 28
2007	13.73	19.23	3.91	9527	14729	- 27
2008	13.53	18.60	4.33	9638	14720	- 36
2016	13.38	19.72	4.42	9583	14886	+130
2017	13.28	18.24	4.56	9797	14833	+ 77
2013	12.48	21.14	5.11	9348	14693	- 63
2014	12.89	18.78	3.78	9742	14880	+124
2029	14.24	19.64	4.47	9431	14829	+ 73
2030	15.90	16.35	3.75	9667	14724	- 32
2031	14.11	17.36	3.97	9677	14591	-165
2032	13.66	15.43	3.77	10173	14767	+ 11

* Probably due to error in ash determination.

TABLE 13
COAL RESULTS—(Concluded)

Lab. No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	Variation from Av- erage B. t. u.
	Moisture	Ash	Sulphur	B. t. u.		
2057	13.61	15.71	4.13	10128	14775	+ 19
2071	12.16	18.31	3.98	9986	14856	+100
2072	12.22	18.93	3.93	9857	14821	+ 65
2073	13.10	20.38	3.99	9520	14864	+108
2074	12.47	19.37	4.04	9791	14892	+136
2106	13.31	17.49	4.03	9816	14660	— 96
2107	14.07	17.50	4.43	9742	14739	— 17
2108	13.12	17.25	4.41	9987	14837	+ 81
2145	12.81	16.82	3.98	10066	14764	+ 8
2146	13.97	15.64	4.76	9813	14632	—124
2147	13.19	17.68	4.21	9805	14668	— 68
2159	13.30	17.98	4.17	9831	14805	+ 49
2160	12.20	20.14	4.78	9628	14805	+ 49
2161	13.12	17.61	4.34	9900	14790	+ 34
2178	14.83	19.77	3.90	9319	14793	+ 37
2179	14.01	17.92	4.13	9858	14993	+237*
2180	13.03	19.92	4.11	9503	14710	— 46
2232	14.07	17.40	4.12	9815	14813	+ 57
2233	13.26	19.54	4.25	9381	14483	—273*
2234	12.26	18.90	3.95	9611	14446	—310*
2235	13.02	17.94	4.46	9706	14547	—209
2304	15.07	19.03	4.42	9346	14730	— 26
2305	14.22	16.93	4.81	9718	14614	—142
2324	15.16	16.98	3.72	9706	14771	+ 15
2325	15.33	16.60	3.77	9792	14849	+ 93
2326	11.99	19.10	4.13	9801	14735	— 21
2369	12.00	18.42	3.92	9900	14712	— 44
2370	14.29	18.74	4.63	9498	14727	— 29
2371	13.28	17.33	4.17	9897	14744	— 12
2416	13.55	18.55	4.48	9630	14706	— 50
Av....	13.30	17.79	4.18	9828	14756	± 86

* Probably due to error in ash determination.

TABLE 14
COAL RESULTS
Run-of-Mine Coal from Two Mines, Boulder Co., Colo.

No.]	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
					B. t. u. — 5000S	
					1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
13	19.59	8.38	.52	9349	13118	+120
15	20.18	8.15	.39	9362	13193	+195
19	20.26	6.85	.38	9434	13053	+ 55
20	19.64	6.83	.36	9519	13054	+ 56
22	19.49	7.23	.48	9580	13192	+194
24	19.43	5.77	.38	9625	12958	— 40
25	19.12	7.16	.42	9620	13164	+166
27	20.43	6.40	.36	9512	13102	+104
30	19.65	8.55	.41	9271	13048	+ 50
31	19.91	6.75	.38	9425	12958	— 40
35	20.32	7.85	.44	9431	13260	+262
37	19.71	4.88	.38	9779	13046	+ 48
5	20.23	5.81	.35	9373	12761	—237
7	19.73	5.08	.29	9598	12842	—156
8	19.64	5.97	.30	9497	12859	—139
9	19.83	5.54	.29	9573	12911	— 87
13	20.06	5.51	.33	9551	12917	— 81
18	20.08	4.82	.38	9632	12902	— 96
19	19.96	5.63	.30	9588	12972	— 26
34	19.99	6.55	.40	9441	12955	— 43
38	19.38	5.11	.27	9712	12939	— 59
42	19.96	6.95	.25	9422	12998	00
45	20.56	5.60	.26	9428	12853	—145
76	18.09	5.56	.41	9835	12907	— 91
Av.....	19.80	6.37	.36	9523	12998	±104

TABLE 15

COAL RESULTS

Run-of-Mine Coal from One Mine, Las Animas Co., Colo.

No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
	Moisture	Ash	Sul.	B. t. u.	B. t. u. — 5000S	
					1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
2	2.25	9.72	.89	13309	15288	— 4
10	2.40	11.33	.68	13066	15334	+ 42
12	2.51	14.49	.68	12547	15359	+ 67
14	2.63	11.32	.61	13033	15332	+ 40
15	2.93	11.53	.61	13065	15465	+173
16	2.57	12.81	.60	12842	15386	+ 92
21	2.80	20.17	.65	11643	15468	+176
23	2.26	9.45	.60	13297	15214	— 78
25	2.43	14.86	.60	12572	15448	+156
33	2.02	11.14	.63	13025	15144	—148
37	2.95	13.01	.59	12532	15121	—171
41	3.65	12.22	.63	12584	15159	—133
44	2.48	12.77	.58	12722	15218	— 74
46	2.19	11.57	.61	12904	15150	—142
Av.	2.58	12.59	.64	12796	15292	±107

TABLE 16
ILLINOIS "No. 2" COAL

Lab. No.	LOCALITY	Total Mois- ture	REFERRED TO DRY COAL			"Unit Coal" Basis
			Ash	Sul.	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
1764	Bureau Co.....	15.61	9.59	4.29	13008	14657
1769	Bureau Co.....	15.99	8.96	4.04	13191	14743
1860	Brown Co.....	15.60	10.02	6.01	13099	14904
1869	Christian Co.....	11.54	10.08	4.38	13148	14912
1811	Fulton Co.....	15.37	7.55	3.67	13558	14888
1839	Green Co.....	14.93	12.43	5.79	12581	14739
1840	Green Co.....	15.04	12.38	6.03	12538	14687
733	Grundy Co.....	14.69	8.17	3.62	13217	14616
1787	Grundy Co.....	17.18	6.82	3.11	13450	14622
734	Grundy Co.....	14.16	5.82	1.83	13436	14395
1861	Hancock Co.....	13.48	6.88	4.29	13516	14744
1875	Jackson Co.....	14.25	4.99	.79	14113	14943
1878	Jackson Co.....	12.73	4.75	.71	14115	14902
1876	Jackson Co.....	9.00	6.87	2.02	13799	14975
1765	La Salle Co.....	14.03	9.77	3.36	13033	14686
1785	La Salle Co.....	12.41	8.89	3.23	13329	14858
1768	LaSalle Co.....	15.36	14.03	5.34	12241	14618
1775	Marshall Co.....	14.60	7.29	1.90	13539	14761
1795	Marshall Co.....	13.54	6.66	2.90	13743	14908
1831	McDonough Co.....	16.42	8.18	3.23	13418	14829
1748	Mc Lean Co.....	12.02	10.13	3.36	12980	14704
1857	Mercer Co.....	17.56	11.58	5.47	12666	14669
1411	Peoria Co.....	12.05	10.90	4.48	12866	14739
1802	Warren Co.....	18.52	5.45	3.20	13650	14606
1793	Woodford Co.....	16.18	8.33	3.55	13361	14802

TABLE 17
ILLINOIS "No. 5" COAL FROM SOUTHERN PART OF STATE

Lab. No.	LOCALITY	Total Mois- ture	REFERRED TO DRY COAL			"Unit Coal" Basis
			Ash	Sul.	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
1092	Gallatin Co.....	4.47	10.85	3.72	13235	15133
1094	Saline Co.....	6.03	10.54	3.12	13212	15024
1095	Saline Co.....	4.89	11.49	4.16	12931	14916
1110	Saline Co.....	4.34	12.68	6.12	12879	15157
1111	Saline Co.....	6.64	9.21	2.35	13367	14927
1112	Saline Co.....	6.10	8.99	3.52	13415	15019
1113	Saline Co.....	5.97	7.62	2.30	13700	15011
1114	Saline Co.....	4.43	9.04	2.47	13450	14993
1115	Saline Co.....	6.04	11.58	3.26	12942	14911
1116	Saline Co.....	6.13	9.89	2.37	13298	14973
896	Williamson Co.....	6.29	10.68	3.86	13073	14930
1809	Williamson Co.....	6.47	12.53	3.62	12853	15000

TABLE 18

ILLINOIS "No. 5" COAL FROM CENTRAL PART OF STATE

Lab. No.	LOCALITY	Total Mois- ture	REFERRED TO DRY COAL			"Unit Coal" Basis
			Ash	Sul.	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
1404	Fulton Co.....	15.09	12.52	3.79	12450	14527
1807	Fulton Co.....	15.03	12.98	2.95	12389	14510
1808	Fulton Co.....	15.49	13.43	3.81	12364	14594
1856	Fulton Co.....	15.44	12.22	4.17	12666	14740
1771	La Salle Co.....	13.13	12.19	4.15	12544	14590
1788	Livingston Co.....	12.73	12.15	3.67	12853	14929
1569a	Macon Co.....	13.91	11.33	3.82	12549	14427
1874	Macon Co.....	14.07	11.82	4.28	12545	14529
1749	Mc Lean Co.....	12.56	14.06	4.74	12299	14672
1847	Mc Lean Co.....	14.15	13.54	2.82	12485	14725
1848	Menard Co.....	15.55	12.20	3.58	12590	14627
1403	Peoria Co.....	14.29	15.46	3.16	12094	14635
1407	Peoria Co.....	13.86	16.25	3.91	12044	14755
1408	Peoria Co.....	13.91	15.23	3.39	12189	14713
1409	Peoria Co.....	13.45	16.66	3.58	12014	14786
1410	Peoria Co.....	14.73	14.78	3.97	12257	14730
540	Sangamon Co.....	13.56	10.76	4.78	12749	14589
721	Sangamon Co.....	14.39	13.64	4.61	12304	14593
740	Sangamon Co.....	14.30	12.75	4.11	12369	14468
741	Sangamon Co.....	13.13	12.47	4.28	12416	14495
1794	Sangamon Co.....	13.69	14.26	3.88	12133	14477
1761	Sangamon Co.....	14.61	12.48	4.55	12364	14444
1762	Sangamon Co.....	14.56	12.85	4.54	12281	14415
1766	Sangamon Co.....	15.42	14.73	4.19	12082	14515
1767	Sangamon Co.....	15.53	12.68	3.83	12340	14427
1770	Sangamon Co.....	14.89	11.32	4.79	12663	14591
1772	Sangamon Co.....	14.00	12.83	4.06	12358	14486
1773	Sangamon Co.....	14.44	11.71	4.85	12477	14447
1774	Sangamon Co.....	14.41	11.80	5.09	12550	14557
1786	Sangamon Co.....	14.18	14.67	5.00	12115	14574
1790	Sangamon Co.....	16.41	10.69	3.65	12685	14477
1791	Sangamon Co.....	15.44	12.91	4.01	12301	14430
1792	Sangamon Co.....	15.38	10.14	4.00	12849	14578
1812	Schuyler Co.....	12.99	12.76	4.31	12709	14899
1868	Shelby Co.....	11.26	13.63	4.93	12373	14686
1412	Tazewell Co.....	14.30	11.49	3.90	12690	14623
1413	Tazewell Co.....	14.35	12.45	3.53	12504	14569
720	Logan Co.....	14.80	13.81	3.56	12426	14733
1889	Logan Co.....	11.83	12.25	3.83	12376	14392

TABLE 19
BLUE BAND COAL

Lab. No.	LOCALITY	Total Mois- ture	REFERRED TO DRY COAL			"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Ash	Sul.	B. t. u.	
742	Christian Co.....	11.82	13.50	4.71	12203	14448
1870	Christian Co.....	15.15	9.97	3.70	12745	14405
1871	Christian Co.....	14.88	10.67	4.04	12696	14484
996	Clinton Co.....	10.97	10.47	4.80	12815	14614
997	Clinton Co.....	13.05	13.98	5.29	12232	14596
1177	Clinton Co.....	15.19	11.15	1.65	12569	14342
1178	Clinton Co.....	14.81	16.56	2.99	11639	14262
1175	Clinton Co.....	11.83	10.78	3.96	12659	14459
1176	Clinton Co.....	12.86	13.59	4.52	12246	14512
1845	Edgar Co.....	14.94	11.00	3.02	12890	14734
1846	Edgar Co.....	14.82	11.42	3.34	12797	14715
461	Franklin Co.....	14.40	8.08	1.19	13400	14722
419	Franklin Co.....	11.19	10.11	.60	12985	14597
420	Franklin Co.....	10.06	7.53	.91	13312	14519
1810	Franklin Co.....	10.13	10.29	.78	12945	14590
1722	Franklin Co.....	8.47	10.55	2.13	12778	14491
1723	Franklin Co.....	9.09	8.78	1.21	13173	14595
1776	Franklin Co.....	9.11	6.42	1.33	13620	14679
1777	Franklin Co.....	8.48	7.32	1.33	13527	14734
1799	Jackson Co.....	7.81	13.20	3.85	12650	14897
1800	Jackson Co.....	9.14	10.22	.68	12970	14603
1651	Jefferson Co.....	7.48	11.35	3.34	12824	14735
1652	Jefferson Co.....	7.85	12.10	4.19	12611	14655
735	Macoupin Co.....	12.80	10.86	5.38	12469	14301
736	Macoupin Co.....	12.71	11.40	4.41	12360	14238
737	Macoupin Co.....	12.17	12.87	5.48	12303	14477
738	Macoupin Co.....	12.80	11.90	4.33	12440	14419
1841	Macoupin Co.....	12.89	12.68	6.49	12214	14369
1862	Macoupin Co.....	13.93	12.29	5.23	12371	14441
725	Madison Co.....	11.68	11.22	4.85	12762	14692
1117	Madison Co.....	10.33	10.59	4.12	12681	14457
1118	Madison Co.....	14.16	13.65	2.81	12114	14303
1119	Madison Co.....	11.20	11.72	5.17	12499	14485
1866	Marion Co.....	10.31	14.96	5.61	12167	14720
1842	Montgomery Co.....	13.61	8.50	4.37	13473	14990
1864	Montgomery Co.....	12.84	10.58	4.30	12743	14534
1863	Montgomery Co.....	14.76	9.98	4.60	12712	14398
1873	Montgomery Co.....	13.21	11.51	4.90	12570	14522
421	Perry Co.....	9.31	14.71	.98	12181	14517
1523	Perry Co.....	11.03	12.63	1.01	12453	14456
1614	Perry Co.....	10.37	13.92	3.93	12293	14607
1615	Perry Co.....	9.87	13.86	3.28	12261	14534
1591	Perry Co.....	11.11	15.89	4.34	11859	14471
1592	Perry Co.....	10.49	12.17	3.84	12361	14359
1835	Perry Co.....	10.55	12.12	4.50	12393	14412
1610	Randolph Co.....	10.72	14.55	5.07	11978	14385

TABLE 19
BLUE BAND COAL—(Concluded)

Lab. No.	LOCALITY	Total Mois- ture	REFERRED TO DRY COAL			"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Ash	Sul.	B. t. u.	
1616	Randolph Co.....	9.93	13.41	5.36	12245	14505
1120	Saline Co.....	5.98	13.79	3.73	12505	14830
722	Sangamon Co.....	14.96	11.04	4.55	12640	14503
1763	Sangamon Co.....	14.69	10.98	4.95	12503	14349
739	Sangamon Co.....	13.14	12.23	5.03	12372	14425
723	St. Clair Co.....	12.11	12.23	4.37	12604	14676
724	St. Clair Co.....	12.23	9.69	3.33	12982	14612
991	St. Clair Co.....	9.76	15.80	4.76	12202	14895
995	St. Clair Co.....	10.05	12.47	4.19	12587	14694
993	St. Clair Co.....	9.44	11.23	4.37	12723	14630
1001	St. Clair Co.....	13.75	12.53	2.13	12486	14512
1002	St. Clair Co.....	13.15	13.43	3.23	12290	14486
1003	St. Clair Co.....	9.41	12.94	4.90	12701	14948
1129	St. Clair Co.....	15.91	11.07	4.70	12706	14593
1130	St. Clair Co.....	11.11	12.00	4.72	12587	14625
1174	St. Clair Co.....	15.46	12.73	4.02	12428	14549
1600	St. Clair Co.....	11.43	15.14	5.69	11908	14435
557	Vermilion Co.....	12.56	9.15	1.41	13058	14537
558	Vermilion Co.....	12.96	8.03	1.78	13304	14626
1540	Vermilion Co.....	17.73	11.95	1.15	12561	14463
1843	Vermilion Co.....	13.23	11.43	3.17	12842	14761
1844	Vermilion Co.....	13.41	9.76	3.52	13083	14748
1643	Washington Co.....	10.41	11.34	4.35	12468	14351
1121	White Co.....	6.71	11.50	4.46	12744	14708
459	Williamson Co.....	9.99	8.48	1.03	13323	14701
460	Williamson Co.....	9.50	10.13	1.12	13078	14724
1088	Williamson Co.....	6.69	10.65	2.50	13016	14795
462	Williamson Co.....	9.39	7.66	1.89	13475	14754
1611	Williamson Co.....	10.15	9.73	1.06	13229	14763
1612	Williamson Co.....	6.12	13.76	4.42	12461	14799
1567	Williamson Co.....	6.80	11.84	2.96	12788	14770
1613	Williamson Co.....	9.69	10.23	1.16	13077	14742
1801	Williamson Co.....	9.75	8.13	1.71	13438	14791
1805	Williamson Co.....	7.58	12.10	3.85	12698	14745
1806	Williamson Co.....	9.79	9.85	2.19	13048	14676
1804	Williamson Co.....	6.77	13.29	5.08	12517	14800
1917	Williamson Co.....	8.86	9.65	1.15	13103	14685
1918	Williamson Co.....	9.34	9.50	1.74	13172	14739

APPENDIX A

TABLE 20

UNIT COAL VALUES

Compiled from Bulletin 9, Fourth Series, 1908, Ohio State Geological Survey

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
		Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)

CLARION OR NO. 4 COAL

65	Lawrence.....	6.34	17.41	5.29	10741	14562
67	Lawrence.....	5.86	15.28	5.36	11133	14547
68	Lawrence.....	6.11	9.94	3.61	11957	14508
66	Lawrence.....	6.00	11.86	5.10	11734	14645
64	Scioto.....	6.80	9.34	3.45	11763	14272
63	Jackson.....	4.90	13.70	6.14	11495	14545
62	Jackson.....	5.31	13.54	6.08	11381	14436
55	Jackson.....	5.61	8.09	3.70	12279	14465
56	Jackson.....	4.98	9.80	4.08	12154	14538
57	Jackson.....	4.71	8.61	3.73	12361	14505
60	Jackson.....	5.33	8.40	3.72	12206	14387
59	Vinton.....	4.72	11.21	4.16	12049	14640
61	Vinton.....	4.52	8.85	4.23	12337	14505
54	Vinton.....	5.02	8.15	2.81	12469	14639
58	Vinton.....	4.61	11.10	5.28	12053	14645
70	Vinton.....	5.02	8.97	3.32	12528	14780
69	Vinton.....	4.95	9.32	3.53	12445	14775
	Average.....	5.34	10.80	4.33	11947	14551

LOWER KITTANING OR NO. 5 COAL

74	Lawrence.....	7.57	8.79	3.20	12199	14830
75	Lawrence.....	8.07	9.71	2.13	11927	14727
76	Jackson.....	8.39	7.42	2.65	12190	14679
71	Perry.....	6.85	10.16	4.72	11864	14612
72	Perry.....	6.74	7.12	2.58	12393	14574
73	Muskingum.....	5.05	7.77	4.80	12569	14691
77b	Jefferson.....	2.46	7.40	3.82	13664	15406
77	Tuscarawas.....	5.30	7.71	3.25	12902	15061
77a	Mahoning.....	5.23	4.72	2.17	13504	15141
	Av.....	6.18	7.87	3.26	12578	14863

MIDDLE KITTANING OR NO. 6 COAL

136	Lawrence.....	5.99	4.82	3.61	13165	14957
82a	Lawrence.....	6.64	10.92	3.32	11927	14749
82b	Gallia.....	8.08	8.52	3.64	12091	14753
89a	Athens.....	6.36	8.49	0.51	12454	14764
83	Athens.....	6.17	7.82	0.90	12362	14511
84	Athens.....	6.70	6.75	2.28	12458	14563

TABLE 20
UNIT COAL VALUES—(Continued)

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
		Mois- ture	Ash	Sul- phur	B. t. u.	
						B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
85	Athens.....	6.80	8.05	2.14	12229	14547
82	Vinton.....	4.90	10.15	4.25	12321	14802
81	Hocking.....	6.52	8.03	3.52	12330	14666
89	Athens.....	7.14	6.72	1.65	12353	14488
90	Athens.....	7.28	6.73	0.86	12409	14552
86	Hocking.....	7.55	5.85	0.77	12510	14552
87	Hocking.....	7.45	4.81	0.66	12703	14563
88	Hocking.....	7.40	5.00	1.06	12649	14542
80	Hocking.....	6.55	6.97	2.57	12422	14548
79	Perry.....	7.76	7.47	1.45	12190	14534
91	Perry.....	5.79	5.91	1.00	12569	14510
78	Perry.....	7.00	6.95	2.33	12384	14569
92	Perry.....	5.25	9.86	3.43	12191	14620
93	Perry.....	5.90	10.10	4.96	12035	14649
95	Perry.....	6.72	6.64	2.43	12425	14513
94	Perry.....	7.21	5.26	2.34	12614	14562
97	Perry.....	5.70	8.45	3.38	12332	14600
98	Perry.....	6.40	7.58	2.72	12361	14569
101	Muskingum.....	5.08	9.77	5.54	12244	14716
100	Muskingum.....	4.67	9.83	4.10	12371	14756
96	Muskingum.....	5.02	9.56	5.97	12164	14581
99	Muskingum.....	5.44	9.28	3.77	12280	14663
104	Muskingum.....	5.55	5.23	3.63	12944	14703
102	Muskingum.....	4.75	9.28	5.35	12337	14668
103	Muskingum.....	4.62	6.58	4.49	12827	14689
111	Coshocton.....	4.37	5.36	3.61	13045	14643
112	Coshocton.....	10.93	6.64	2.03	11039	13871*
108	Coshocton.....	4.33	5.59	4.00	13084	14736
109	Coshocton.....	5.12	7.02	3.87	12719	14708
105	Coshocton.....	5.32	6.30	4.22	12755	14661
110	Coshocton.....	5.60	13.28	4.87	11200	14159
113	Coshocton.....	4.44	4.45	3.54	13232	14702
114	Coshocton.....	4.58	8.75	5.36	12380	14589
118	Coshocton.....	5.32	8.60	4.36	12290	14546
120	Coshocton.....	4.50	5.97	3.63	12911	14623
107	Coshocton.....	5.40	5.08	3.18	12949	14641
133	Tuscarawas.....	3.45	7.67	5.22	12843	14733
131	Tuscarawas.....	3.41	9.38	4.88	12548	14686
115	Tuscarawas.....	4.72	5.47	4.05	12958	14637
130	Tuscarawas.....	3.78	8.42	3.83	12782	14808
129	Tuscarawas.....	3.81	6.01	3.24	13151	14774
124	Tuscarawas.....	4.10	5.21	3.25	13196	14730
134	Tuscarawas.....	3.18	6.93	4.12	13149	14865
116	Tuscarawas.....	5.19	5.87	3.55	12820	14613
128	Tuscarawas.....	4.30	7.63	3.97	12602	14546

* Low B. t. u. due to weathering.

TABLE 20
UNIT COAL VALUES—(Continued)

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
		Mois- ture	Ash	Sul- phur	B. t. u.	
117	Coshocton.....	4.70	11.29	5.60	11869	14481
106	Coshocton.....	5.30	6.15	3.72	12751	14609
121	Tuscarawas.....	3.52	6.01	3.17	13135	14705
122	Tuscarawas.....	4.94	9.50	4.19	12341	14706
123	Tuscarawas.....	3.51	7.69	4.56	12875	14761
132	Carroll.....	3.76	6.79	3.06	13028	14760
138	Tuscarawas.....	7.15	4.56	2.62	12949	14820
127	Tuscarawas.....	4.66	6.22	3.28	12775	14525
119	Holmes.....	7.31	4.21	1.00	12514	14230
125	Tuscarawas.....	4.69	9.06	4.70	12386	14649
126	Tuscarawas.....	4.92	7.04	2.91	12748	14676
135	Stark.....	6.66	8.22	2.66	12559	14971
137	Columbiana.....	3.60	4.60	1.76	14020	15401
139	Stark.....	5.65	10.08	4.13	12362	14973
	Av.....	5.56	7.36	3.30	12564	14644

UPPER FREEPORT, WATERLOO OR NO. 7 COAL

147	Lawrence.....	7.20	10.67	2.33	11801	14824
144	Lawrence.....	7.85	12.18	2.66	11349	14465
145	Lawrence.....	8.37	8.23	1.29	11873	14396
146	Lawrence.....	8.45	11.28	0.93	11529	14547
142	Gallia.....	7.62	12.39	1.81	11468	14586
140	Lawrence.....	7.13	8.91	1.31	12089	14570
141	Lawrence.....	8.77	8.71	0.76	11855	14517
143	Lawrence.....	8.38	10.09	1.84	11695	14556
	Av.....	7.97	10.31	1.62	11707	14531

UPPER FREEPORT OR NO. 7 COAL

148	Muskingum.....	4.89	7.78	4.36	12499	14566
149	Muskingum.....	4.72	7.56	5.00	12683	14736
150	Muskingum.....	5.11	12.60	3.84	11804	14667
151	Coshocton.....	6.40	3.19	2.01	13185	14694
	Av.....	5.28	7.78	3.80	12542	14665

TABLE 20
UNIT COAL VALUES—(Continued)

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
		Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
PITTSBURG OR No. 8 COAL						
25	Gallia.....	5.80	10.06	4.34	11792	14301
27	Gallia.....	6.98	9.03	5.21	11849	14413
28	Gallia.....	7.83	9.76	3.89	11779	14575
26	Gallia.....	6.73	13.03	4.37	11441	14614
23	Athens.....	5.78	8.00	4.19	12299	14618
24	Athens.....	6.60	10.20	3.41	11892	14560
24	Athens.....	4.51	11.49	4.88	11945	14553
22	Morgan.....	6.87	8.19	4.22	12100	14504
9	Belmont.....	2.79	9.42	5.09	12987	14134
11	Belmont.....	4.08	10.61	4.95	12476	14961
8	Belmont.....	2.91	8.00	4.31	13212	15099
3	Belmont.....	3.51	6.86	3.76	13185	14937
4	Belmont.....	3.80	8.95	4.27	12785	14933
7	Belmont.....	3.21	7.26	4.28	13135	14920
10	Belmont.....	4.47	11.01	4.67	12375	14976
6	Belmont.....	3.75	10.84	4.76	12357	14794
5	Belmont.....	4.46	10.76	4.45	12425	14977
1	Belmont.....	3.39	7.86	2.97	12991	14850
2	Belmont.....	3.79	9.00	4.16	12861	15027
6a	Belmont.....	4.25	10.35	3.95	12425	14840
2a	Belmont.....	4.23	9.21	4.17	12605	14842
12	Jefferson.....	3.10	9.52	3.83	12875	15008
15	Jefferson.....	3.13	8.22	4.02	13019	14943
15a	Jefferson.....	4.57	9.00	1.55	12789	14980
18	Harrison.....	6.54	6.74	2.19	12710	14829
21	Harrison.....	5.98	5.97	1.35	12964	14853
20	Harrison.....	3.83	10.88	4.38	12355	14798
16	Jefferson.....	4.89	10.46	4.09	12515	15095
13	Jefferson.....	4.96	6.45	1.75	13099	14938
19	Jefferson.....	4.18	8.22	2.83	12888	14928
14	Jefferson.....	4.30	7.88	3.01	12859	14858
17	Jefferson.....	5.05	7.95	2.61	12865	14995
	Av.....	4.70	9.10	3.81	12559	14835
POMEROY OR No. 8a COAL						
34	Gallia.....	8.21	11.46	2.18	11497	14561
33	Meigs.....	4.85	12.52	2.94	11923	14718
29	Meigs.....	7.33	8.69	2.05	12105	14608
30	Meigs.....	7.22	9.29	1.32	12002	14552
31	Meigs.....	5.51	10.58	4.17	11990	14588
32	Meigs.....	7.63	10.93	1.83	11722	14618
	Av.....	6.79	10.58	2.42	11873	14608

TABLE 20
UNIT COAL VALUES—(Concluded)

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
		Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
MEIGS CREEK OR NO. 9 COAL						
53	Washington.....	2.95	12.89	5.55	12245	14946
52	Washington.....	3.40	9.58	5.03	12749	14970
44	Noble.....	3.06	12.33	6.00	12357	15011
45	Noble.....	2.90	10.16	4.27	12692	14895
43	Noble.....	2.55	11.41	5.79	12514	14918
42	Noble.....	3.12	12.85	5.60	12130	14827
50	Morgan.....	5.13	11.74	4.89	11925	15270
48	Morgan.....	5.05	10.37	4.30	12114	14621
49	Morgan.....	4.07	10.66	5.07	12202	14637
47	Noble.....	3.54	13.23	6.21	11956	14787
46	Noble.....	4.85	9.82	5.59	12301	14757
37	Belmont.....	4.47	13.07	3.27	12002	14870
40	Belmont.....	3.40	14.94	4.39	11840	14890
41	Belmont.....	3.52	11.84	3.67	12391	14947
39	Belmont.....	4.17	9.60	3.11	12602	14863
38	Belmont.....	4.31	11.68	1.94	12307	14888
36a	Belmont.....	7.52	11.24	2.11	11860	14846
36	Belmont.....	4.98	12.82	2.41	11974	14846
35	Harrison.....	5.35	10.29	2.20	12393	14919
	Av.....	4.11	11.60	4.28	12240	14845

APPENDIX B

TABLE 21

UNIT COAL VALUES

Compiled from Bulletins 261, 290, 332, United States
Geological Survey

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Mois- ture	Ash	Sul- phur	B. t. u.	
							B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
ALABAMA							
1	1078M*	Walker.....	1.35	13.63	.71	12991	15509
1	1201C *	Walker.....	2.34	12.54	.72	12856	15313
2	1075M	Walker.....	2.25	9.04	1.09	13133	14967
2	1076M	Walker.....	2.42	11.13	1.10	12695	14879
2	3011M	Walker.....	4.71	10.17	1.33	12596	14992
2	1225C	Walker.....	3.36	12.43	1.01	12350	14879
2	3211C	Walker.....	3.95	14.59	1.12	11785	14722
3	3018M	Bibb.....	3.03	10.72	.49	13034	15285
3	3255C	Bibb.....	2.72	14.36	.55	12461	15263
4	3034M	Bibb.....	3.67	3.14	1.22	14396	15536
4	3103C	Bibb.....	6.43	12.92	1.08	12395	15616
5	4091M	Blount.....	2.93	2.73	.65	14693	15636
5	4252C	Blount.....	5.59	16.08	1.40	11906	15518
6	4293M	Jefferson.....	2.81	3.51	.59	14643	15701
5	4338C	Jefferson.....	3.23	6.71	.61	14074	15747
ARKANSAS							
1	1045M	Sebastian.....	1.02	7.49	1.10	14434	15927
1	2585M	Sebastian.....	3.53	7.77	1.29	14017	15971
1	1114C	Sebastian.....	3.24	12.61	1.24	13129	15846
1	2689C	Sebastian.....	7.49	17.97	1.06	11369	15604
2	1049M	Sebastian.....	.95	6.97	2.12	14387	15806
2	1160C	Sebastian.....	2.23	9.20	1.87	13750	15733
3	1115M	Sebastian.....	1.60	7.91	1.42	14162	15818
3	1296C	Sebastian.....	2.19	11.63	1.28	13464	15849
5	1130M	Franklin.....	1.38	6.95	1.52	14330	15790
5	1331C	Franklin.....	2.36	12.08	1.99	13259	15761
7	2593M	Sebastian.....	3.97	5.91	1.53	14236	15945
7	2688C	Sebastian.....	5.47	11.69	2.02	12690	15582
7	2722C	Sebastian.....	6.89	15.00	2.24	12060	15787
8	2587M	Johnson.....	3.12	8.46	1.84	13793	15797
8	2744C	Johnson.....	5.19	14.01	2.05	12460	15731
9	2599M	Sebastian.....	1.99	7.06	1.05	14087	15628
9	2690C	Sebastian.....	5.26	24.81	1.00	10451	15434
10	2647M	Ouachita.....	39.50	12.58	.53	5877	12551
10	2726C	Ouachita.....	39.43	9.71	.49	6356	12717
13	3798M	Franklin.....	2.91	17.51	3.12	12312	15898
13	4626C	Franklin.....	1.76	14.96	2.29	12926	15853

* Samples marked M are mine samples: those marked C are car samples of various sizes of coal.

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis	
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S	
							1.00 — (1.08 Ash + ²² / ₄₀ S.)	
CALIFORNIA								
1	1607M	Alameda	18.02	16.37	3.07	8105	12699	
1	1680C	Alameda	18.51	15.49	3.05	8507	13243	
COLORADO								
1	1383M	Boulder	20.02	3.61	.52	10237	13477	
1	1523C	Boulder	18.68	5.99	.55	10143	13570	
FLORIDA								
1	3270C	Orange	21.00	5.17	.45	8127	11076	
GEORGIA								
1	4156M	Chattanooga . . .	2.85	7.84	.67	14198	16039	
1	4320C	Chattanooga . . .	3.80	14.49	1.27	12791	15939	
ILLINOIS								
24	2854M	Clinton	13.43	9.18	3.35	10937	14395	
24	2972C	Clinton	11.44	10.71	4.94	10958	14422	
25	2856M	Clinton	11.64	8.66	3.41	11290	14416	
35	2991C	Clinton	11.35	13.40	4.76	10733	14666	
23	4385M	Clinton	15.06	9.65	1.05	10726	14435	
10	1648C	Franklin	9.50	11.44	1.45	11506	14783	
13	1694M	Franklin	9.46	8.12	1.63	11990	14745	
13	1786C	Franklin	8.31	10.48	1.55	11727	14651	
19	1871M	Franklin	9.90	7.74	.48	12001	14699	
19	1926C	Franklin	14.91	8.93	.52	10958	14545	
19	2020C	Franklin	10.72	9.36	.91	11686	14800	
18	1741M	La Salle	13.87	10.31	3.44	10985	14790	
18	1779C	La Salle	12.39	8.92	3.92	11399	14784	
26	3003	Logan	15.68	12.09	3.51	10215	14482	
9	1625M	Macoupin	13.29	8.90	4.12	11162	14641	
9	1635C	Macoupin	13.54	10.74	4.03	10807	14599	
9	1639C	Macoupin	13.72	10.32	3.96	10870	14627	
9	4247C	Macoupin	15.25	15.35	3.81	9790	14528	
20	2731C	Macoupin	14.68	13.68	3.88	10053	14409	
4	1341M	Madison	15.09	7.42	.83	11151	14533	
4	1417C	Madison	12.91	11.64	1.32	10804	14552	

TABLE 21

UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Mois- ture	Ash	Sul- phur	B. t. u.	
5	1556C	Madison.....	17.02	16.79	3.29	9319	14523
7	1609M	Madison.....	11.87	11.58	4.75	10768	14425
7	1611C	Madison.....	11.46	17.31	4.40	10026	14542
7	1780C	Madison.....	10.83	13.18	4.53	10816	14618
21	2770M	Madison.....	15.23	9.03	1.59	10901	14595
21	2852C	Madison.....	15.54	10.93	1.38	10507	14517
22	2772M	Madison.....	13.51	10.15	4.01	10881	14566
22	2905C	Madison.....	11.91	13.01	5.34	10615	14554
22	2896C	Madison.....	13.03	14.53	4.35	10192	14480
23	2774M	Madison.....	13.07	10.06	3.59	10949	14535
23	2819C	Madison.....	13.47	11.53	4.41	10510	14360
23	2803C	Madison.....	15.68	15.59	3.98	9655	14483
29	3911M	Madison.....	14.25	9.44	3.72	10892	14566
29	3913M	Madison.....	12.69	8.76	3.62	11236	14571
29	3958C	Madison.....	12.47	12.56	4.37	10667	14602
29	3963C	Madison.....	13.10	16.00	4.17	9983	14519
29	3980C	Madison.....	12.25	12.33	4.42	10719	14578
15	1725M	Marion.....	10.25	12.53	3.70	11077	14683
15	1761C	Marion.....	9.95	13.23	3.87	10960	14622
6	1449M	Montgomery...	14.89	7.87	3.61	11016	14518
6	1661M	Montgomery...	12.90	11.08	3.78	10856	14602
6	1557C	Montgomery...	14.43	13.28	4.01	10064	14290
6	1702C	Montgomery...	11.93	14.18	4.29	10303	14332
8	1627C	Montgomery...	13.20	12.53	4.47	10514	14673
1	1095M	St. Clair.....	11.17	10.32	4.22	11223	14612
1	1261C	St. Clair.....	9.75	13.20	4.10	11025	14675
2	1152C	St. Clair.....	12.03	22.44	4.00	9149	14542
30	3912M	St. Clair.....	9.88	10.81	3.83	11439	14733
30	4364C	St. Clair.....	11.69	13.19	4.38	10699	14625
31	4251M	St. Clair.....	14.38	8.75	3.13	10858	14375
31	4376C	St. Clair.....	13.10	13.25	3.66	10363	14423
14	1704M	Sangamon.....	13.89	11.26	3.83	10636	14540
14	1740C	Sangamon.....	12.77	11.78	4.16	10757	14607
27	2897M	Sangamon.....	14.29	8.18	4.41	11007	14488
27	3052C	Sangamon.....	16.00	13.77	4.05	9940	14554
34	4414M	Saline.....	7.51	7.48	1.58	12686	15091
34	4636C	Saline.....	9.33	11.89	2.76	11572	14984
34	4622C	Saline.....	7.81	8.38	2.36	12418	15029
3	1170M	Williamson....	7.50	7.15	.99	12386	14646
3	1318C	Williamson....	8.50	11.28	1.72	11776	14916
11	1634M	Williamson....	8.30	9.26	2.82	11999	14794
11	1654C	Williamson....	7.76	10.61	1.97	11957	14835
11	1660C	Williamson....	8.86	11.66	2.46	11702	14956
11	1718C	Williamson....	8.61	7.66	1.65	12236	14797
12	1683M	Williamson....	8.29	10.83	2.81	11837	14867
12	1762C	Williamson....	8.20	12.95	3.48	11362	14740

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Mois- ture	Ash	Sul- phur	B. t. u.	
12	4201C	Williamson . . .	15.87	9.52	2.34	10784	14701
12	3907C	Williamson . . .	12.61	10.50	2.37	11066	14647
12	4085C	Williamson . . .	15.31	10.47	2.32	10820	14846
16	1731M	Williamson . . .	9.37	7.37	1.25	12058	14632
16	1820C	Williamson . . .	8.43	9.60	1.14	11959	14772
28	3629M	Williamson . . .	8.72	7.62	1.00	12200	14727
28	3789C	Williamson . . .	7.78	9.98	1.32	11959	14770
INDIANA							
20	3536M	Clay	15.38	5.88	1.95	11680	15004
20	3979C	Clay	16.91	17.37	1.89	9524	14900
15	3473M	Greene	13.53	7.55	.95	11738	15028
15	3567C	Greene	13.58	8.15	.91	11419	14749
16	3564C	Greene	10.30	11.75	4.23	11218	14737
17	3516M	Knox	10.60	8.30	3.69	11752	14754
17	3981C	Knox	12.08	11.02	3.65	11011	14630
10	1853M	Parke	11.54	9.62	4.41	11655	15116
10	1979C	Parke	10.72	8.57	3.83	11767	14857
19	3534M	Parke	13.70	5.91	2.66	11930	15036
7	1824M	Pike	10.18	8.12	3.96	12181	15193
7	1881C	Pike	8.90	9.21	3.74	12008	14946
7	1882C	Pike	11.12	9.35	3.78	11549	14811
12	2701M	Pike	11.29	6.87	3.09	11921	14772
12	2759C	Pike	10.57	11.65	3.87	11266	14818
18	3525M	Pike	12.88	6.14	1.70	11801	14728
18	3801C	Pike	11.13	6.98	1.64	12031	14856
1	1410M	Sullivan	13.25	9.16	1.87	11360	14857
1	1507C	Sullivan	11.40	13.40	2.50	11061	15032
4	1775M	Sullivan	14.86	7.35	2.26	11324	14759
4	1844C	Sullivan	13.99	14.32	2.31	10318	14730
5	1773M	Sullivan	12.14	8.96	3.54	11516	14875
5	1859C	Sullivan	12.03	10.88	4.27	11192	14726
6	1772M	Sullivan	10.45	9.58	4.04	11745	14995
6	1875C	Sullivan	10.80	12.62	4.39	11185	14990
11	1883M	Sullivan	14.23	5.72	.89	11722	14764
11	2087C	Sullivan	12.15	8.14	1.41	11761	14934
8	1828M	Vigo	10.68	12.24	4.38	11261	14984
8	2037C	Vigo	9.55	10.61	3.72	11759	15042
9	1848M	Vigo	13.73	8.65	3.00	11360	14891
9	1960C	Vigo	13.53	10.76	3.15	10948	14759
9	1973C	Vigo	12.82	10.30	3.27	11119	14752
13	3467M	Vigo	13.43	7.34	2.16	11448	14642
13	3748C	Vigo	12.97	12.09	3.18	10899	14871
14	3491M	Vigo	13.62	7.11	3.28	11543	14797
14	3775C	Vigo	7.88	14.20	5.14	11146	14725

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
2	1425M	Warrick.....	9.28	9.34	4.44	11799	14806
2	1495C	Warrick.....	9.62	13.02	4.43	11122	14754
3	1759M	Warrick.....	11.28	7.63	3.58	11792	14792
3	1941C	Warrick.....	13.18	15.63	4.79	10030	14547
IOWA							
1	1270M	Davis.....	11.35	10.51	4.72	11345	14871
1	1347C	Davis.....	8.24	16.00	5.03	11027	15026
2	1289M	Marion.....	15.65	11.64	5.10	10289	14548
2	1570C	Marion.....	14.21	15.22	4.66	10019	14652
3	1312M	Polk.....	14.42	10.99	5.89	10640	14680
3	1434C	Polk.....	13.88	14.01	6.15	10244	14698
4	1323M	Appanoose....	17.13	7.07	4.00	10931	14694
4	1437C	Appanoose....	14.08	10.96	4.26	10723	14650
5	1332M	Lucas.....	18.69	7.73	2.39	10505	14496
5	1433C	Lucas.....	15.39	12.63	3.19	10242	14567
INDIAN TERRITORY							
		(Town)					
1	1059M	Henryetta....	8.87	8.63	1.62	12096	14848
1	1138C	Henryetta....	7.04	10.01	1.92	12202	14929
2	1071M	Hartshorne....	1.46	6.40	1.38	14040	15375
2	1184C	Hartshorne....	4.45	11.00	1.52	12607	15129
3	1080M	Edwards.....	2.93	10.30	3.73	12591	14786
3	1274C	Edwards.....	4.61	11.14	3.63	12319	14918
4	1151M	Lehigh.....	6.50	9.31	3.67	11842	14318
4	1470C	Lehigh.....	6.24	13.21	3.96	11228	14267
5	1481C	Lehigh.....	8.29	25.05	3.95	9110	14264
9	4020C	Panama.....	5.11	8.03	1.18	13662	15897
KANSAS							
		(County)					
1	1018M	Crawford.....	2.91	9.55	3.79	12947	15063
1	1097C	Crawford.....	4.99	12.97	4.28	12242	15293
2	1017M	Crawford.....	2.44	10.60	5.63	13043	15373
2	1122C	Crawford.....	4.18	17.91	6.27	11642	15511
3	1037M	Cherokee.....	2.54	9.87	4.47	13340	15535
3	1086C	Cherokee.....	2.50	12.45	5.68	12900	15589
4	1473C	Atchison.....	6.95	12.19	8.04	11905	15244
5	1411M	Cherokee.....	5.11	8.90	4.34	12926	15332
5	1567C	Cherokee.....	4.10	10.54	3.77	12895	15412
6	2790M	Linn.....	11.13	12.60	2.41	11219	15011
6	2843C	Linn.....	9.04	15.72	3.72	11142	15231

TABLE 21

UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis	
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)	
KENTUCKY								
1	1321M	Bell.....	2.91	3.53	.89	14322	15280	
1	2350M	Bell.....	3.42	3.18	1.53	14375	15491	
1	1474C	Bell.....	3.10	4.39	1.22	14148	15397	
1	2445C	Bell.....	5.21	8.22	1.12	13214	15427	
2	1365M	Hopkins.....	8.49	7.10	3.53	12344	14858	
2	1461C	Hopkins.....	7.91	9.13	3.62	12200	14979	
3	1367M	Hopkins.....	7.98	9.30	4.03	11965	14748	
3	1506C	Hopkins.....	7.92	10.06	3.52	12022	14944	
4	1382M	Webster.....	4.61	7.40	3.33	12861	14836	
4	1539C	Webster.....	5.27	14.18	4.54	11950	15240	
5	2270M	Harlan.....	4.32	2.28	.48	14121	15165	
5	2528C	Harlan.....	4.36	3.70	.67	13923	15217	
6	2405M	Johnson.....	6.95	2.03	.48	13687	15054	
6	2592C	Johnson.....	5.12	2.76	.57	13743	14975	
7	2453M	Muhlenberg.....	8.76	9.42	4.07	11965	14919	
7	2595C	Muhlenberg....	8.47	9.48	3.60	11986	14886	
8	3678M	Union.....	7.46	4.60	.97	13489	15443	
8	3860C	Union.....	5.46	7.92	1.18	13239	15444	
9	3722M	Ohio.....	10.03	7.67	2.56	12076	14758	
9	3723M	Ohio.....	9.89	8.69	2.45	11927	14872	
9	3865C	Ohio.....	8.70	8.96	3.14	12078	14922	
MARYLAND								
1	2018M	Garrett.....	2.47	9.55	1.23	13853	15936	
1	2274C	Garrett.....	2.33	13.13	1.49	13255	15942	
MISSOURI								
1	1043M	Bates.....	4.92	14.52	5.34	11992	15334	
1	1126C	Bates.....	8.33	19.36	5.25	10586	15209	
2	1226M	Macon.....	14.74	7.78	3.79	11185	14705	
2	1348C	Macon.....	11.50	16.86	5.16	10179	14709	
3	1549C	Putnam.....	15.71	20.78	3.69	8840	14471	
4	1446M	Morgan.....	13.34	6.91	5.06	11605	14855	
4	1516C	Morgan.....	12.67	4.83	5.12	12487	15426	
5	2795M	Randolph.....	13.38	10.02	4.48	11084	14808	
5	2865C	Randolph.....	12.92	13.62	5.03	10548	14793	
6	2817M	Randolph.....	14.01	10.29	5.23	11030	14955	
6	2904C	Randolph.....	13.80	11.74	5.60	10796	14929	
7	2823M	Adair.....	17.19	9.28	2.76	10598	14677	
7	2936C	Adair.....	16.36	19.51	3.53	9007	14566	
7	2942C	Adair.....	17.30	23.38	2.94	8240	14496	
7	2937C	Adair.....	16.39	20.18	3.12	8946	14626	
10	4197M	Macon.....	15.41	11.61	3.78	10582	14853	
10	4257C	Macon.....	15.23	20.50	3.69	9099	14712	

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
MONTANA							
1	1298C	Carbon.....	11.05	10.97	1.73	10539	13727
2	4234C	Carbon.....	8.51	15.39	.60	10478	14017
3	4271C	Carbon.....	8.56	13.39	.54	10685	13899
NEW MEXICO							
1	(1025)M						
	(1026)M	McKinley.....	10.96	4.01	.52	11885	14048
1	1278C	McKinley.....	12.29	6.99	.63	11252	14058
2	1028M	McKinley.....	9.68	8.08	1.55	11623	14301
2	1307C	McKinley.....	10.79	18.66	1.26	9907	14398
3	3221M	Colfax.....	2.50	9.13	.72	13127	15006
3	3295C	Colfax.....	3.45	16.67	.73	11893	15173
3	3307C	Colfax.....	4.36	15.92	.83	11912	15220
3	3308C	Colfax.....	2.75	15.52	.64	12166	15141
4	3228M	Colfax.....	2.19	11.11	.57	13063	15246
4	3331C	Colfax.....	2.78	14.57	.61	12294	15113
4	3315C	Colfax.....	3.38	13.54	.61	12445	15202
5	3226M	Colfax.....	2.25	12.37	.75	13030	15472
5	3294C	Colfax.....	2.72	14.57	.69	12539	15408
NORTH DAKOTA							
1	1971M	Stark.....	42.06	7.66	1.13	6158	12441
1	1279C	Stark.....	35.38	9.35	1.55	6923	12756
1	2289C	Stark.....	32.64	11.42	3.54	6970	12798
2	1730M	Williams.....	41.13	5.36	.72	6485	12242
2	1416C	Williams.....	36.78	5.09	.48	7204	12496
2	2365C	Williams.....	36.13	5.04	.59	7326	12558
3	1935M	McLean.....	40.53	5.05	.76	6644	12325
3	2243C	McLean.....	35.96	7.75	1.15	7069	12740
OHIO							
6	2095M	Belmont.....	3.99	8.07	3.49	13102	15144
6	2392C	Belmont.....	5.31	8.52	3.33	12843	15153
11	3986M	Belmont.....	4.13	7.96	4.12	13088	15155
11	4157C	Belmont.....	3.44	12.94	4.32	12287	15049
12	4151C	Belmont.....	4.14	9.38	3.96	12874	15172
12	4178C	Belmont.....	2.97	9.97	3.65	12933	15133
7	2090M	Guernsey.....	6.28	7.30	3.55	12701	14930
7	2656C	Guernsey.....	6.65	10.55	3.13	12179	14984

TABLE 21

UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Mois- ture	Ash	Sul- phur	B. t. u.	
1	1896M	Jackson.....	8.45	6.73	3.10	12249	14647
1	2071C	Jackson.....	7.71	11.95	4.61	11515	14685
2	1898M	Jackson.....	9.38	7.62	4.08	11898	14590
2	2109C	Jackson.....	9.01	11.34	4.02	11495	14758
4	1910M	Jefferson.....	4.06	7.75	3.67	13147	15152
4	2083C	Jefferson.....	3.53	9.12	3.47	13072	15226
5	1944M	Jefferson.....	4.69	6.01	1.54	13325	15060
5	2062C	Jefferson.....	4.34	7.30	1.72	13178	15078
3	1900M	Perry.....	10.78	6.13	1.11	11993	14563
3	2144C	Perry.....	9.90	11.58	1.81	11277	14605
8	2119M	Perry.....	8.92	5.85	3.00	12328	14653
8	2559C	Perry.....	7.55	8.37	2.84	12128	14644
10	3969M	Tuscarawas....	4.46	8.54	3.73	12845	15022
10	4059C	Tuscarawas....	4.49	7.53	2.93	12958	14938
9	2208M	Vinton.....	6.79	7.66	3.34	12514	14858
9	2310C	Vinton.....	5.59	8.29	3.15	12773	15068
9	2311C	Vinton.....	8.10	11.93	3.35	11563	14766

PENNSYLVANIA

10	2080M	Allegheny.....	3.67	5.46	1.37	13874	15395
10	2229C	Allegheny.....	2.61	6.17	1.26	13997	15475
13	3437M	Allegheny.....	2.53	8.98	2.21	13356	15303
13	3879C	Allegheny.....	2.65	13.16	2.16	12816	15507
8	2014M	Cambria.....	3.49	5.71	.95	14515	16108
8	2152C	Cambria.....	3.51	6.63	.94	14279	16025
16	4029M	Cambria.....	2.74	7.23	1.51	14144	15876
16	4169C	Cambria.....	4.25	7.87	1.59	13513	15553
18	4348M	Cambria.....	2.66	8.56	2.97	13995	16014
18	4509C	Cambria.....	4.46	8.47	1.49	13682	15903
21	4412M	Fayette.....	2.82	7.37	1.22	13991	15731
21	4609C	Fayette.....	5.13	8.71	.86	13365	15675
15	4027M	Indiana.....	2.84	8.27	3.11	14079	16094
15	4082C	Indiana.....	3.13	9.81	3.77	13795	16159
15	4104C	Indiana.....	2.57	10.33	3.97	13712	16072
17	4337	Indiana.....	2.22	8.42	1.54	13801	15624
17	4421	Indiana.....	4.35	11.90	1.51	12964	15725
9	2016M	Somerset.....	2.63	10.21	2.05	13705	15963
9	2199C	Somerset.....	3.09	11.33	2.04	13424	15945
5	1966M	Washington....	3.01	4.83	.73	14197	15499
5	2068C	Washington....	2.46	6.05	.88	14013	15430
11	3421M	Washington....	2.50	5.34	1.14	14146	15465
11	3532C	Washington....	1.95	7.29	1.18	13775	15320
12	3441M	Washington....	2.60	5.63	1.19	14184	15689
12	4098C	Washington....	1.96	9.25	2.19	13622	15560

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Mois- ture	Ash	Sul- phur	B. t. u.	
4	1942M	Westmoreland..	2.73	9.13	1.33	13613	15629
4	2187C	Westmoreland..	3.15	10.41	1.26	13406	15714
6	1968M	Westmoreland..	4.08	9.50	1.64	13268	15557
6	2161C	Westmoreland..	3.24	12.52	1.94	12879	15555
7	1994M	Westmoreland..	3.30	11.18	1.79	13378	15887
7	2154C	Westmoreland..	4.09	12.47	2.08	13153	16050
19	4352M	Westmoreland..	2.01	6.32	1.39	14152	15579
19	4489C	Westmoreland..	3.39	8.36	1.05	13699	15685
20	4350M	Westmoreland..	2.48	9.24	3.03	13822	15936
20	4517C	Westmoreland..	4.00	10.54	2.85	13347	15899
22	4498C	Westmoreland..	3.98	10.16	1.00	13311	15693

TENNESSEE

1	2907M	Claiborne.	3.71	4.74	1.28	13804	15195
1	3016C	Claiborne.....	4.81	11.15	1.58	12569	15180
2	2931M	Campbell.....	3.61	3.41	.83	14130	15271
2	3129C	Campbell.....	5.09	6.81	.98	13295	15222
3	2929M	Campbell.....	4.25	4.13	.93	13666	15004
3	3040C	Campbell.....	5.38	7.05	.99	13048	15033
4	2956M	Roane.....	3.25	6.61	.85	13514	15112
4	3058C	Roane.....	6.39	9.53	.98	12578	15135
5	2958M	Morgan.....	2.25	6.91	2.96	13851	15456
5	3050C	Morgan.....	5.59	9.76	3.23	12841	15445
6	2977M	Cumberland....	3.80	4.50	.78	14182	15557
6	3102C	Cumberland....	3.89	14.43	.78	12514	15574
7	2979M	Fentress.....	3.46	9.08	2.42	12983	15073
7	3133C	Fentress.....	3.03	12.85	3.26	12602	15300
8	3005M	White.....	3.01	10.76	3.42	13104	15490
8	3127C	White.....	2.63	13.42	4.38	12715	15529
8	3128C	White.....	3.12	14.12	4.74	12517	15540
9	2995M	Grundy.....	3.44	9.21	.73	13219	15292
9	3113C	Grundy.....	3.92	14.09	.94	12508	15510
9	3114C	Grundy.....	5.68	18.55	.74	11480	15489
9	3115C	Grundy.....	4.68	9.26	.65	13163	15454
10	3009M	Marion.....	3.31	13.11	1.30	12193	15825
11	3471C	Cumberland....	3.53	27.87	.90	10264	15514

TEXAS

1	1196M	Houston.....	33.50	10.75	.56	7142	13034
1	1456C	Houston.....	34.70	11.20	.79	7056	13298
2	1241M	Wood.....	28.86	7.92	.50	7996	12794
2	1597C	Wood.....	33.71	7.28	.53	7348	12594

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Moisture	Ash	Sulphur	B. t. u.	
3	2652M	Milan.....	36.01	7.38	.77	7132	12759
3	2734C	Milan.....	31.06	7.88	.99	7870	13059
4	2635M	Wood.....	36.80	6.25	.53	7101	12598
4	2717C	Wood.....	33.85	7.30	.51	7497	12885
UTAH							
1	3199C	Carbon.....	6.05	4.87	.55	13151	14848
2	3200M	Summitt.....	14.07	6.26	1.28	10471	13262
VIRGINIA							
1	2268M	Lee.....	5.69	8.11	2.31	13117	15428
1	2420C	Lee.....	4.06	4.73	1.20	13826	15267
2	2476C	Lee.....	3.35	5.58	.92	13932	15410
3	2382C	Wise.....	3.05	4.48	.67	14470	15736
4	2323M	Lee.....	3.89	3.06	.34	14144	15253
4	2358C	Lee.....	4.35	4.33	.79	13939	15353
5	4093M	Montgomery...	2.98	21.94	.68	11669	15949
5	4287C	Montgomery...	4.80	18.03	.63	11961	15825
5	4294C	Montgomery...	7.52	16.23	.65	11893	15900
6	4305M	Tazewell.....	2.60	4.48	1.35	14636	15867
6	4573C	Tazewell.....	5.62	9.79	1.21	13264	15880
WASHINGTON							
1	2456M	King.....	17.97	7.78	.43	10006	13604
1	2687C	King.....	16.04	11.53	.61	9938	13920
1	2686C	King.....	14.30	11.37	.72	10208	13930
2	2458M	Kittitas.....	3.39	10.39	.33	12847	15059
2	3098C	Kittitas.....	3.16	12.26	.38	12586	15070
WEST VIRGINIA							
6	1176M	Fayette.....	2.10	3.55	.75	14900	15870
6	1390C	Fayette.....	1.53	5.05	.65	14807	15944
7	1198M	Fayette.....	2.12	3.55	.90	14915	15895
7	1595C	Fayette.....	3.94	4.93	1.16	14382	15898
8	1257M	Fayette.....	1.90	4.87	.64	14452	15591
8	1515C	Fayette.....	4.16	7.17	.90	13786	15686
9	1208M	Fayette.....	1.98	3.76	.85	14738	15825
9	1561C	Fayette.....	4.08	6.58	.77	13925	15712

TABLE 21

UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
13	1867M	Fayette.....	5.48	2.29	.79	14454	15734
13	2028C	Fayette.....	3.74	3.91	.89	14436	15721
14	1870M	Fayette.....	2.96	7.44	1.04	13972	15741
14	2004C	Fayette.....	5.09	3.27	1.03	14110	15480
19	2359M	Fayette.....	3.26	2.46	.78	14773	15733
19	2549C	Fayette.....	2.96	5.01	.89	14425	15780
2	1103M	Harrison.....	1.98	9.08	4.20	13466	15432
2	1308C	Harrison.....	1.95	7.86	3.48	13790	15536
15	2039M	Harrison.....	2.80	5.55	2.40	14105	15558
15	2195C	Harrison.....	2.01	8.55	2.54	13811	15664
20	2375M	Kanawha.....	2.66	4.44	1.14	14368	15571
20	2556C	Kanawha.....	2.82	8.03	1.38	13766	15609
21	2377M	Kanawha.....	3.57	3.62	1.14	14173	15362
21	2572C	Kanawha.....	3.57	4.85	1.32	13948	15346
22	3456M	Kanawha.....	2.75	5.49	.63	13813	15149
22	3457M	Kanawha.....	3.49	6.44	.63	13813	15449
22	3905C	Kanawha.....	3.42	7.82	.83	13486	15335
23	3458M	Kanawha.....	3.13	3.54	.59	13963	15027
23	3965C	Kanawha.....	2.05	8.10	1.35	13707	15420
23	3625C	Kanawha.....	3.25	7.58	1.22	13523	15317
25	4291M	Kanawha.....	3.91	7.68	.64	13471	15199
25	4360C	Kanawha.....	4.21	7.22	.64	13379	15229
11	1234M	McDowell.....	2.21	5.25	.44	14792	16075
11	1472C	McDowell.....	4.07	11.12	.51	13509	16122
12	1238M	McDowell.....	1.92	4.39	.52	14926	16013
12	1242M	McDowell.....	3.48	3.90	.73	14731	15989
12	1364C	McDowell.....	1.72	6.87	.68	14571	16065
1	1088M	Marion.....	1.40	6.67	1.59	14063	15447
1	1213C	Marion.....	1.75	6.34	.90	14107	15450
16	2041M	Marion.....	2.89	5.71	.69	14540	16020
16	2264C	Marion.....	5.57	8.37	1.20	13093	15701
10	1240M	Mercer.....	2.93	3.62	.48	14924	16039
10	1471C	Mercer.....	1.75	4.58	.56	15023	16125
18	2348M	Mingo.....	2.81	6.50	.66	13957	15504
18	2527C	Mingo.....	2.86	5.83	.67	14106	15554
3	1108M	Monongalia....	2.90	8.19	.75	13941	15829
3	1252C	Monongalia....	2.29	10.23	1.06	13558	15689
4	1116M	Preston.....	2.26	7.74	.85	13999	15697
4	2054M	Preston.....	3.57	6.21	.85	14218	15882
4	1262C	Preston.....	1.48	8.39	.90	14069	15764
4	2250C	Preston.....	3.91	10.11	1.07	13370	15744
17	2056M	Preston.....	3.22	7.33	1.73	13995	15822
17	2332C	Preston.....	3.46	8.12	1.45	13869	15861
5	1144M	Randolph.....	2.82	10.45	1.00	13475	15731
5	1297C	Randolph.....	1.45	10.10	.98	13718	15693

TABLE 21
UNIT COAL VALUES—(Concluded)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis	
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S	
							1.00 — (1.08 Ash + ²² / ₄₀ S.)	
WYOMING								
1	1368M	Sheridan	22.00	3.37	.60	9796	13192	
	1479C	Sheridan	22.63	4.50	.59	9734	13444	
2	1376M	Weston	8.60	21.90	4.94	9709	14550	
	1571C	Weston	9.44	20.72	3.91	9650	14320	
3	2131C	Weston	8.93	20.79	4.03	10001	14757	
	1976M	Crook	17.74	11.55	7.03	9527	13918	
	2278C	Crook	15.12	16.70	6.66	8928	13604	
4	3160M	Carbon	12.32	5.19	.23	11102	13534	
	3363C	Carbon	11.30	7.31	.28	10755	13316	
	3396C	Carbon	12.40	6.77	.26	10706	13341	
5	3164M	Sweetwater	12.41	2.52	.80	11920	14071	
	3213C	Sweetwater	11.64	3.41	.81	11768	13923	
6	3202M	Uinta	20.57	2.63	.51	10237	13383	
	3390C	Uinta	19.00	3.12	.49	10307	13293	
ALASKA								
2479	.....	.....	4.43	4.65	.51	13640	15083	
2483	.....	.....	13.89	7.23	.82	12137	15537	
2219	.....	.....	6.74	12.47	.44	11968	15017	
2222	.....	.....	2.55	6.05	.57	13711	15101	
2224	.....	.....	6.60	10.87	.41	11338	13898	
2227	.....	.....	.90	4.90	.60	14868	15873	
ARGENTINA, SOUTH AMERICA								
4079C	.....	.....	7.67	42.85	1.21	6320	13792	
BRAZIL, SOUTH AMERICA								
172	.....	Dry Coal . . . . .	.....	27.54	3.02	10028	14398	
173	.....	Dry Coal . . . . .	.....	27.84	4.53	9830	14241	

- Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print*).
- Circular No. 1.* High-Speed Tool Steels, by L. P. Breckenridge. 1905. (*Out of print*).
- Bulletin No. 2.* Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. (*Out of print*).
- Circular No. 2.* Drainage of Earth Roads, by Ira O. Baker. 1906. (*Out of print*).
- Circular No. 3.* Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907, by L. P. Breckenridge and Paul Diserens. 1909.
- Bulletin No. 3.* The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (*Out of print*).
- Bulletin No. 4.* Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.
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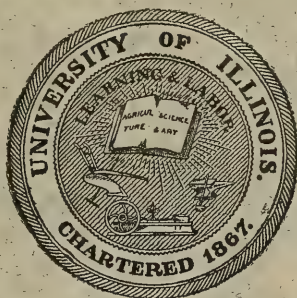
SERIES OF 1909

BY

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AND

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THE WEATHERING OF COAL

By S. W. PARR, PROFESSOR OF APPLIED CHEMISTRY

AND

W. F. WHEELER, FIRST ASSISTANT, DEPARTMENT OF CHEMISTRY,
ENGINEERING EXPERIMENT STATION

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I. INTRODUCTION¹

In February, 1908, there was published by the Engineering Experiment Station of the University of Illinois, Bulletin 17, entitled "The Weathering of Coal." This publication embodied the results of a series of experiments which were intended at the time to be introductory to an extended study of the subject. As was stated in the text (page 14), the experiments were of a preliminary nature, undertaken mainly to gain information for carrying out more elaborate and comprehensive tests. A number of circumstances made it evident to the writers of this bulletin that it would be advisable to make the work undertaken at that time of a purely preliminary nature; for example, it was decided to make use of relatively small samples, the amount being approximately 20 pounds each. It was thought that the indications given by these samples would serve the purpose of avoiding serious mistakes when tests upon larger masses were made. Moreover, while these experiments were in progress, data from another source accumulated, establishing the fact that a rapid deterioration occurred in the coal in the first few days after breaking out from the seam. This fact promised to have a very important bearing upon the changes which ordinarily would be attributed to weathering losses. This phase of the subject was carried out simultaneously by Mr. W. F. Wheeler and was included in the bulletin noted above under the title "Deterioration of Coal Samples." The effect of such deterioration was not established in time to incorporate the procedure indicated by the fact of such losses, in the experiments on the weathering samples. These fundamental reasons are sufficient to indicate the preliminary nature of the first bulletin. It has since been possible to continue the work in a far more satisfactory manner by making use of the experience already gained in the first experiments. The subject, as here presented again under the same title, has the justification, it is hoped, of being fairly well-rounded and complete in so far as is possible by making use of the experience and knowledge of modifying conditions available at the present time. In one phase of the subject, however, it is far from complete. The subject of weathering can not be gone into without involving also the subject of spontaneous combustion. It is along this latter line that the work is being continued, and it is hoped soon

¹ Credit is due Mr. W. F. Wheeler for the greater part of the work embodied in this bulletin. Mr. Wheeler died Nov. 18, 1909.

to bring those experiments to a stage where the results will justify their publication under that title.

II. COAL STORAGE

The storing of coal has become more and more of a necessity in the last few years, owing to market conditions, occasional labor difficulties at the mines and on the railroads, and the crowding of transportation facilities. Of these causes, the first is probably of chief importance. It is due to the variable demand for coal for domestic consumption, which necessitates either a much higher rate of production during the winter months or else the providing of sufficient storage capacity to carry over coal produced in the dull season. Especially is this true in the case of anthracite coal, which suffers the most from a variable demand owing to the fact that a larger proportion of it is used for domestic purposes. Anthracite requires much more expensive plants for its preparation than ordinary bituminous coal, and thus offers greater inducements for the operators to keep the rate of production near the capacity of their equipment. One means of doing this is by inducing the consumers to store coal in the summer months. The scheme at present used for this purpose is a sliding scale of prices with a fixed advance in price per ton for every month from April to September. This plan has worked admirably for a number of years, probably ten million tons of coal being stored each summer by consumers and coal dealers. The anthracite coal companies themselves have a combined storage capacity for about seven million tons, or approximately one tenth of the present annual production. This storage capacity is in very large units, the piles containing from 50 000 to 400 000 tons each.

The bituminous coal producers have a more uniform demand throughout the year for all sizes and grades of their product than the anthracite producers can expect. Large power plants, naval coaling stations and railroads are the principal interests storing bituminous coal, except around the great lakes. At nearly all the cities at the head of lakes, the coal companies themselves store great quantities of coal during the season of navigation. Part of this coal is for local consumption, but a larger part of it is for reshipment by rail.

While market conditions offer one of the principal reasons for storing coal, large manufacturing establishments, most power plants

and various other coal users feel compelled to have on hand a reserve supply that will enable their plants to run without interruption in case of strikes, car shortages and other unforeseen circumstances. For this purpose the amount of coal necessarily stored at different plants varies from a few hundred to a few thousand tons.

Anthracite is the nearest approach to an ideal coal for storage. It is practically unaffected by the weather. It is broken somewhat by handling, and at most of the larger storage plants it must be re-screened as it is reloaded. It is not subject to spontaneous ignition, and in consequence there is practically no limit to the size of the piles in which it can be stored. With bituminous coal, the case is different. Most bituminous coal will ignite spontaneously if placed in large enough piles; all of it suffers more or less disintegration during storage and rehandling. Only the coals least liable to fire and those that stand rehandling the best are stored to any extent by the coal producers. Many of the railroads, power plants, factories and naval coaling stations, however, are forced to store coal that is easily affected by the weather and subject to spontaneous ignition. The greatest losses due to coal storage are due to the firing of the stored coal. The atmospheric oxidation of the coal is going on slowly all the time at ordinary temperatures, and continues with increasing rapidity at higher temperatures, until in many cases it results in the ignition of the coal. Thus it must be seen that coals most readily oxidized by the air are most prone to spontaneous ignition, and are the ones that lose the most in heating value. Any heating of the coal in the pile represents just so much heat that will not be available later under the boiler. Most of the atmospheric oxidation does not produce any sensible heating, but it results, nevertheless, in an appreciable loss of heat units by the coal. The changes taking place in stored coal may be divided into two classes: (1) oxidation of pyrite, marcasite and other inorganic constituents; and (2) the direct oxidation of the organic matter of the actual coal. To the changes in the inorganic matter most of the visible changes are due,—the iron sulphide changes into sulphate of iron and sulphuric acid, the latter of which unites with the calcium and magnesium carbonates, almost invariably present in the coal, to form gypsum and magnesium sulphate. All such changes result in a large increase in volume and a marked disintegration of the coal, and they will also result in a considerable increase in the weight of the coal in many instances unless removed by the

leaching action of water. The other changes due to the direct oxidation of the coal substances cannot be detected by the eye except in rare instances where they have progressed nearly to completion, as in the case of a sample of coal taken from an outcrop in Peoria county, Illinois. (See Table 15). This particular coal has changed from a lustrous black bituminous coal to a dull brown lignite as far as appearances go. It is, however, the invisible change due to this direct oxidation of the carbon and available hydrogen of the coal substance and the absorption of the oxygen by unsaturated hydrocarbons that plays the principal part in promoting spontaneous ignition and in causing weathering losses in heating value.

III. HISTORICAL REVIEW

For the past fifty years, many chemists and engineers have been studying and observing the chemical and physical changes occurring in stored coal. Professor Grundmann¹ of Tarnowitz, Germany, published the first record of any extensive experiments to determine the weathering losses of coal. He made use of the percentage of ash in the coal to determine the change in weight that took place, and with that as a basis, decided that the coal in a pile of 300 tons lost 58 per cent in weight in a period of nine months, the greater portion of the loss taking place soon after the coal was placed in storage. Other experiments by the same writer show losses almost as great. Such changes are, however, hardly confirmed by his other observations, i. e., that the specific gravity and the composition of the coal substance, the actual coal, remained unchanged. It is almost a certainty that the explanation for his extreme figures is to be found in a lack of uniformity of the samples employed. The chief benefit derived from Grundmann's experiments comes from the interest which they aroused in the subject and the investigations they initiated.

Reder² at Ornabruck, Germany, was among the first to follow up Grundmann's work. Using the same kind of coal, he found a small increase in weight and no practical changes in the coal. In the case of one German coal, however, he found a loss of about 4 per cent in the calorific value. Professor Varrentrapp³ of Brunswick, Germany, worked at temperatures between 100° C. and 300° C. and found a

¹ Carnall's Ztsch. Vol. X, p. 236, 1862; Oest. Ztsch. f. Berg, u. Hütt Vol. XV, p. 270, 1867; Kerperly Bericht, 1866, p. 33.

² Oest. Ztsch. f. Berg, u. Hütt. Vol. XV, 1867; Reder, Ztsch. d. Ver. deutsch Eng. Vol. X, p. 698, 1866.

³ Dingler's Jour. Vol. 175, p. 156; Vol. 178, p. 379, 1865.

very rapid oxidation of the coal. In three months at 284° C., coal was reduced completely to ash; and at 160° C., he claims to have oxidized more than one-half of the carbon in the same length of time. Present knowledge of the subject, however, would indicate that the temperature of the coal itself must have been considerably higher than 284° C. That would easily have been possible even though the temperature of the oven or containing vessel did not rise above that temperature. In our own experiments on spontaneous ignition, coal kept in an oven at 110° C. has oxidized rapidly enough to raise its own temperature nearly to 200° C. In experiments with coal under ordinary storage conditions, Varrentrapp reports losses in weight and calorific value of 33 per cent for coal exposed to the weather and 12 per cent for that kept under cover. The same coals are said to have lost 45 and 24 per cent respectively in value for gas making. From the lack of confirmation by subsequent work, it seems that improper sampling or some other error must be sought in explanation of the excessive losses reported.

In 1865, Fleck¹ analyzed a series of six German coals that had been in a cabinet for eleven years, exposed to the air. The samples were not uniform as regards ash contents, but on the ash and water-free coal, the samples all showed a small decrease in carbon and available hydrogen and an increase in oxygen. Richters² soon afterward investigated the action of oxygen on coal at ordinary and moderately raised temperatures. His conclusions are that the coal absorbs oxygen and gives off carbon dioxide and water in smaller amounts, thus leaving a portion of the oxygen combined with the coal substance, causing an increase in weight. The reaction was found to be more rapid at slightly raised temperatures, and it seemed to be unaffected by the amount of moisture present except that in the presence of pyrites the coal was more disintegrated and seemed more liable to heat. Richters found three different coals to lose as much as 3.6 per cent in calorific value in two weeks at about 80° C. He concludes that pyritic coals oxidize most when damp, and that coals free from pyrite are most affected if kept dry. Richters also placed several hundred pounds of fresh coal from different mines in baskets containing about one hundred pounds each, and buried these baskets in a large unprotected pile of coal. After about ten months' storage,

¹Technik d. Steinkohlen Deutschlands, Vol. II, p. 221, 1865.

²Dingler's Jour. Vol. 190, p. 398, 1868.

he found changes in weight varying from a loss of .5 per cent to a gain of 2.0 per cent in the various lots.

Professor Fischer ¹ of Gottingen comes to the same conclusion that was reached by Fleck and Richter, viz., that weathering and spontaneous ignition are due to oxidation of the coal substance and also of the pyrite and marcasite.

Groves and Thorp ² give practically a summary of the previous investigations as to the nature and extent of weathering, but they also ascribe part of the loss to the liberation of combustible occluded gases and state that serious explosions on coal-laden vessels have resulted from this source. They recommend the shipment of only lump coal as a means of preventing fires on shipboard.

E. C. Pechin ³ made analyses of Connelsville coke after two and five years' storage out of doors and found no changes. He states that the best anthracite will lose part of its carbon, and bituminous coal will lose from 10 to 25 per cent by weight upon exposure, but cites no data in proof of his statements. Professor J. W. Langley, in a discussion of the same paper, offers the opinion that the losses sustained by different types of coal during storage are proportional to their ignition temperatures. He mentions Grundmann's and Varrentrapp's experiments as proof.

R. L. Rothwell ⁴ says, as a result of practical observation, that there appears to be no loss in anthracite coal or eastern bituminous coal except in case of small sizes of bituminous coal. He also reviews Richters', Grundmann's and Varrentrapp's work.

R. S. Hale and H. J. Williams ⁵ report an investigation where they exposed three small samples of bituminous coal for eleven months and found a loss in calorific value of from one-half to one per cent. These samples were from Pennsylvania, Virginia and Maryland.

John Macauley, ⁶ general manager of the Alexandra Docks and Railway, Newport, England, comes to the conclusion, after making practical steaming tests with locomotives, that English coal depreciates from ten to twelve per cent per year in steaming value when stored in England. He states as his opinion that the loss in hot climates would be more nearly twenty-four per cent. If the coal were stored under water, less breakage would result; three per cent is esti-

¹Gas World, April 13, 1901.

²Chemical Technology, Vol. I, p. 82.

³Trans. Am. Inst. Min'g Engs., Vol. I, p. 286, 1872.

⁴Trans. Am. Inst. Min'g Engs., Vol. II, p. 150, 1873.

⁵Trans. Am. Soc. Mech Engs., Vol. XX, p. 333, 1899.

⁶Prac. Eng., Oct. 2, 1903. Eng. (London), Oct. 30, 1903.

mated as being sufficient to cover the losses that would be sustained in one year. He bases his estimate for submerged coal on results obtained by burning coal recovered from wrecks, coal that had been under water continually for as long as ten years. There seems to be no certainty as to the original quality of the sunken coal, and such being the case, comparisons made with fresh coal can be only approximations.

Dr. James P. Kimball,¹ of Lehigh University, gives an excellent review of the work done by Grundmann, Varrentrapp, Richters and others, prior to 1879. He also goes thoroughly into the changes due to oxidation of pyrite and marcasite and considers that their effects have been underestimated. He thinks that the oxidation of marcasite especially is of as much importance as the oxidation of the coal itself. Several instances are given where good coking coal has lost its coking property on account of weathering action. Weathering of coal in the seam is mentioned, and analyses of coal from the Coalton or No. 7 seam in Kentucky are presented to show the extent of weathering due to exposure in the mine and also to lack of sufficient cover. As only the proximate analyses are given, together with the analyses of the soluble mineral matter, no material changes are made evident except an increased amount of sulphates of iron and calcium.

In an article by G. Arth,² a report is made of experiments with small coal stored in the air and under water. The conclusions given are that for a period of one year the changes in composition and calorific value are too small to receive practical consideration.

Several practical engineers consider that coal stored for use in locomotives loses from 10 to 50 per cent in heating value, but none of them presents data.

Practically all coal is stored in piles in the open air. The Western Electric Company³ at their Hawthorn plant in Chicago has, however, put in concrete-lined bins, or rather reservoirs, with a capacity of about 15 000 tons of coal. In these bins the coal is kept constantly submerged, primarily for protection from spontaneous ignition. Analyses of coal stored at this plant for two years both under water and in the open air show an advantage of 1.9 per cent in heating value in favor of the coal stored under water.

¹Trans. Am. Inst. Min'g Eng. Vol. VIII, p. 204, 1879.

²Bulletin Soc. Chem., Vol. XI. p. 619-622, 1894.

³Eng. News, Vol. 60, p. 729, 1908.

Several experiments have been made in the last few years by the coaling stations of the United States Navy and also the English Navy to determine the advantages, if any, to be obtained by storing coal under water, but as yet no reports of these experiments have come to our notice.

Dr. Habermann¹ states that the weathering and spontaneous ignition of coal are due to the property of the coal substance for absorbing oxygen. He gives the results of a series of experiments on spontaneous ignition where coal placed in a fire-brick retort at 50° C., and supplied with air at an ordinary temperature, practically ignited in forty-eight hours. Dr. Habermann also found great loss in gas making, coking and heating value.

An editorial in Power² gives Heidepin credit for showing that spontaneous ignition and weathering are due to direct oxidation of the coal substance and to the oxidation of pyrites, as Leibig supposed. Bunte also credits the phenomena to a direct oxidation and absorption of oxygen by the coal. The smaller sizes and the most porous coal are said to be affected the most. The absorption of oxygen may result in a gain in weight of as much as four per cent. W. A. Powers, chief chemist of the Santa Fe Railroad, in 1907, carried out an investigation of the weathering losses of the coals used on that road. These coals covered a wide range of country, samples being tested from Illinois, Missouri, Kansas, Colorado and New Mexico. One hundred-pound lots of coal were stored in the open air and under water for a period of seven months. The coal stored under water is said to have lost from .26 per cent to 5.92 per cent in weight, and from .56 per cent to 8.75 per cent in calorific value. The coal stored in the open air lost in weight .60 per cent to 4.78 per cent and 1.10 per cent to 9.40 per cent in calorific value.

E. A. Tessenden and J. R. Wharton³ state that the higher the percentage of volatile matter in a coal, the more prone it is to spontaneous ignition and the greater the weathering losses it will sustain. Occluded combustible gases, high sulphur content, small size, presence of moisture, high temperature, and free access of air are all given as causes of weathering and fires. Mention is made of the general schemes commonly employed for handling stored coal in open

¹Jour. Gasbel, Vol. 49, p. 419.

²Power, Vol. 27, p. 437, 1907.

³Bulletin University of Mo., Eng. Series, Vol. 1, 1908.

piles and in covered bins. They also note the plans used and proposed to reduce the liability of spontaneous ignition.

In their experimental work only one kind of coal, (from Staunton, Illinois) was used, but it was subjected to different storage conditions, namely, out of doors, in a warm dry room, and under water. Three sizes were prepared and used, making nine samples in all. The coal stored out of doors is said to have disintegrated badly, while that in water and in the dry room was not much damaged. Only the calorific value of the coal as sampled is made use of in determining the weathering losses. The results reported show the futility of trying to make accurate comparisons of the calorific values of fuels on an air-dry basis, with variable ash content. It seems practically certain that the exceedingly high losses found are due largely to discrepancies in the amounts of moisture and ash in the coal samples taken for analysis. Taking the average values for all of the samples used, the losses found in four months were 4.3 per cent for coal under water, 7.0 per cent for coal in dry rooms, and 14.1 per cent for exposed coal. Further experiments are being carried out on samples of Missouri coal, and in them the moisture and ash will be determined in addition to the calorific value.

In the fall of 1906, Mr. N. D. Hamilton,¹ under the direction of Professor S. W. Parr, began a preliminary series of experiments at the University of Illinois to determine the nature and amount of the chemical changes that take place in coal when it is exposed to the weather and also when it is more or less protected. This work extended over a period of nine months. The samples used were collected at the retail coal yards in Champaign and Urbana, Illinois. Most of the coal had been out of the mine for two weeks or more before sampling, time enough for material changes to have taken place, as will be shown later. There was some question as to the exact identity of the coal in the case of a few of the samples. The coal was not sampled and handled in such a manner as to make it representative of any particular product of the mines supplying it. However, that is of but slight importance, except that all of Mr. Hamilton's samples represent small coal and not lump coal, as was reported in some cases. It does not seem at all probable that the so-called lump coal would give the same results likely to be obtained on storing lump coal, as Mr. Hamilton broke the lumps up into pieces about one inch in diameter before storing. It seems very probable also that the

¹Bulletin 17, Eng. Exp. Sta., 1907.

changes taking place in such small lots of coal (about twenty pounds were used in each test), would be very much greater than would occur in actual storage practice, where it would be the exception to find a pile containing as little as two hundred tons. Mr. Hamilton's figures probably would represent only the outside layers of actual coal piles. If the coal in the storage pile becomes very warm, or ignites spontaneously, then the loss and chemical changes taking place may be in excess of changes in the small samples, but that will be the exceptional case. The various samples taken from the 20-lb. lots for analysis were not representative of even that small amount, as great variations occur in the ash and sulphur percentages reported.

In the last three investigations by Mr. Powers, Messrs. Tessenden and Wharton, and Mr. Hamilton, the Parr calorimeter was used exclusively, and probably it is responsible for some erroneous calorific values, owing to the effects of variable amounts of ash and sulphur on the rise in temperature observed in that instrument, some of which were not fully appreciated at the time. A study has been made recently¹ of these errors and it is now possible to correct for them with a fair degree of accuracy.

No account was taken of the amount of disintegration or of changes in weight during Mr. Hamilton's investigation. The tentative conclusions from his work were that coal stored dry or in the open would lose from 2 per cent to 10 per cent in calorific value in a period of nine months, the rate of loss being greatest at first. The coal stored under water did not lose appreciably in calorific value.

IV. STORAGE CONDITIONS

Object of the Experiments.—The object of these experiments was to determine the change in weight, the change in calorific value and the amount of disintegration that are liable to occur in the grades of coal found in Illinois and neighboring states under different conditions of storage, (1) in the open air in piles; (2) in covered bins; and (3) under water.

Source of Coal Tested.—The coal used in these experiments came entirely from Illinois mines. (1) For the principal series, coal from Vermilion, Sangamon and Williamson counties was used, as it was considered representative of about as great a difference in character as is shown by the coals of the State. The results on this series are

¹Jour. Am. Chem. Soc., Vol. 29, p. 1606, 1907.

embodied in Tables 1 to 12 inclusive. (2) Piles of coal of approximately 300 or 400 tons in amount from Christian and Fulton counties were available, and these were examined after they had been exposed for about six months. The results are shown in Table 13. (3) A 15-ton lot of Vermilion county coal had been piled on the ground for $2\frac{1}{2}$ years. Occasional analyses of it had been made and also of some of the same lot which had been stored under water in a barrel by Mr. Hamilton. This pile was resampled; the results of both analyses are embodied in Table 14. (4) A series of samples was taken from old pillars long exposed to mine conditions, as well as the more extreme case of an outcrop. These results are embodied in Table 15. (5) The Commonwealth Edison Company early in 1908, stored nearly 40 000 tons of coal from Williamson and Franklin counties. Advantage was taken of their offer to supply us with samples for experimental purposes. The results are embodied in Table 16.

Storage Conditions, Sizes of Coal and Sizes of Piles Employed.—

As was noted, the principal series consisted of car lots from representative mines in Vermilion, Sangamon and Williamson counties. Carloads of both screenings and nut coal were shipped to the University in January, 1908. One-half of each carload was piled out of doors to a uniform depth of about three and one-half feet, in shallow bins with earth floors. The other half carload was put in covered wooden bins, partly open on two sides, with board floors one and one-half feet above the ground. The coal filled these bins to a depth of about five feet. (See Fig. 1 and 2 for view of storage bins.) Facilities were not available for the storage of any large quantity of coal under water, and on that account only about one hundred pounds from each car was stored in this way. Stone-ware jars were used for containers. The jars, loosely covered to keep out the dust and to retard evaporation, were placed in the basement of the Chemistry building, where the temperature did not vary much from 70° F. The coal from Christian and Fulton counties was not inspected when it was stored, as it was not intended for experimental purposes. It was in piles three to seven feet in depth containing about 500 tons of screenings, entirely exposed to the weather. The coal stored by the Commonwealth Edison Company was in three piles, the main one containing about 25 000 tons of egg coal over three inches and less than six inches in diameter. The second pile contained 3500 tons of nut coal, and the third about 4500 tons of No. 1 washed coal. The



Fig. 1

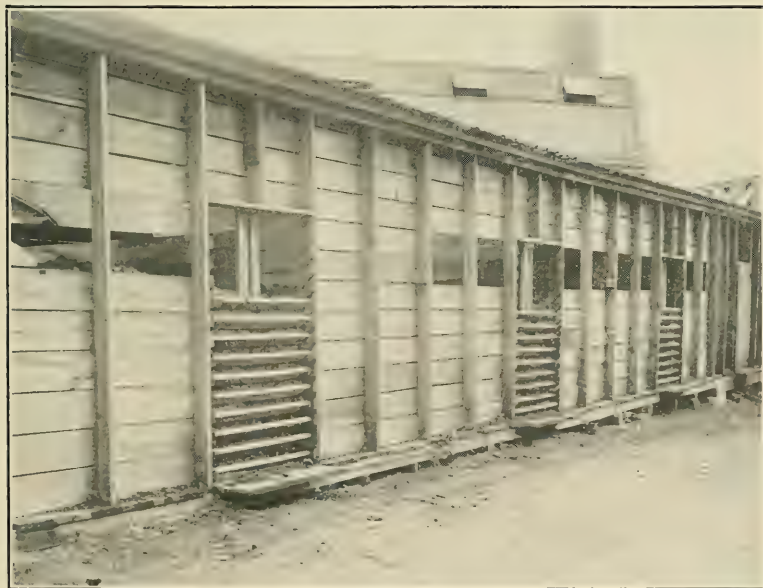


Fig. 2

pillar coal and that from the outcrop in Peoria county are all samples representing the entire thickness of the coal seam. The conditions and time of exposure are given in the tables following, (p. 15).

Sizing Tests.—It was thought that the amount of disintegration suffered by the coal would probably be one of the principal sources of loss, as it might change a coal of suitable size for use in a certain plant to a smaller size than could be used economically. When the coal was stored samples were screened to find the proportion of the various sizes from $\frac{1}{8}$ inch in diameter up to 1 inch and over. The screen used was of the revolving or trommel type, made of perforated steel plate. (See Fig. 3.)

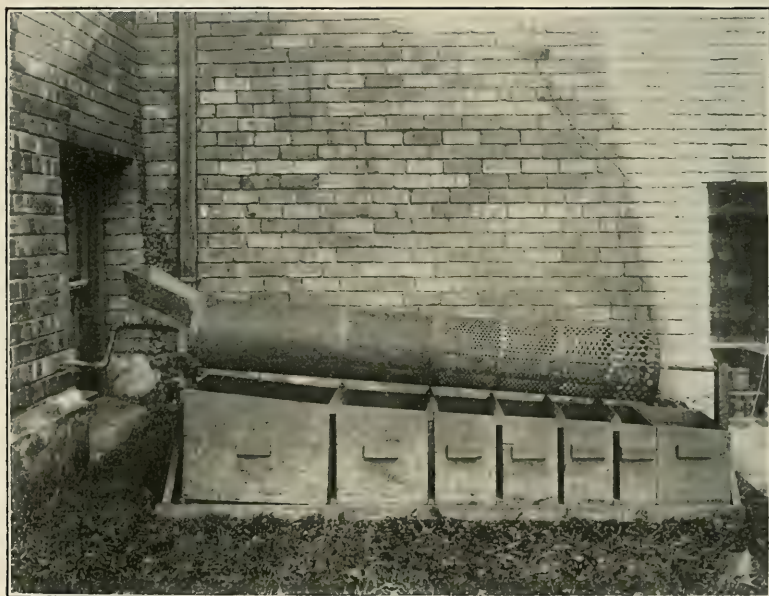


Fig. 3

The relative sizes of coal before and after storing for one and one-half years are shown in Tables 1 and 2 and also graphically in Fig. 4 and 5.

Explanation of Tables.—In the columns headed “per cent.,” Tables 1 and 3, the figures represent the amount of coal between the two sizes given in the same line. The columns headed “cumulative

TABLE 1
SIZING TEST ON NUT COAL
Vermilion County, Illinois

Round Hole Screen		Original Sizes		Exposed Bins 1½ Years		Covered Bins 1½ Years	
Through inches	Over inches	per cent	Cumulative per cent	per cent	Cumulative per cent	per cent	Cumulative per cent
3	1	66.2	.....	42.5	.....	44.2	.....
1	¾	5.0	71.2	8.0	50.5	7.6	51.8
¾	½	7.2	78.4	11.8	62.3	11.7	63.5
½	⅜	4.0	82.4	6.9	69.2	6.7	70.2
⅜	¼	4.0	86.4	6.8	76.0	7.1	77.3
¼	⅛	5.0	91.4	10.9	86.9	10.4	87.7
⅛	0	8.6	100.0	13.1	100.0	12.3	100.0
Total.....		100.0	.....	100.0	.....	100.0	.....
Average diameter....		1.458 in.		1.074 in.		1.102 in.	

Williamson County, Illinois

3	1	94.0	.....	70.2	.....	68.5	.....
1	¾	1.6	95.6	5.7	75.9	5.7	74.2
¾	½	1.8	97.4	6.6	82.5	7.1	81.3
½	⅜	.7	98.1	3.1	85.6	4.1	85.4
⅜	¼	.5	98.6	3.2	88.8	3.6	89.0
¼	⅛	.5	99.1	4.6	93.4	4.9	93.9
⅛	0	.9	100.0	6.6	100.0	6.1	100.0
Total.....		100.0	.....	100.0	.....	100.0	.....
Average diameter....		1.910 in.		1.532 in.		1.506 in.	

Sangamon County, Illinois

3	1	89.4	.....	64.3	.....	52.0	.....
1	¾	4.1	93.5	6.9	71.2	9.3	61.3
¾	½	3.5	97.0	8.4	79.6	10.8	72.1
½	⅜	1.2	98.2	3.2	82.8	5.7	77.8
⅜	¼	.6	98.8	4.0	86.8	5.8	83.6
¼	⅛	.6	99.4	7.4	94.2	8.1	91.7
⅛	0	.6	100.0	5.8	100.0	8.3	100.0
Total.....		100.0	.....	100.0	.....	100.0	.....
Average diameter....		1.854 in.		1.442 in.		1.252 in.	

per cent" give the total amount of coal larger than the smaller of the two sizes given in that line.

The proportion of small sizes in the nut coal is shown to have increased considerably, and the average diameter to have decreased in proportion. The amount of coal that would pass a ½-in. hole

TABLE 2
SIZING TEST ON SCREENINGS
Vermilion County, Illinois

Round Hole Screen		Original Sizes		Exposed Bins 1½ Years		Covered Bins 1½ Years	
Through inches	Over inches	per cent	Cumulative per cent	per cent	Cumulative per cent	per cent	Cumulative per cent
1¾	1	19.0	.....	11.3	.....	11.6	.....
1	¾	8.9	27.9	6.3	17.6	6.3	17.9
¾	½	14.8	42.7	12.9	30.5	12.2	30.1
½	⅜	8.5	51.2	9.3	39.8	9.3	39.4
⅜	¼	11.1	62.3	11.8	51.6	11.8	50.2
¼	⅛	16.4	78.7	21.0	72.6	21.0	71.2
⅛	0	21.3	100.0	27.4	100.0	27.8	100.0
Total. ....	.....	100.0	.....	100.0	.....	100.0	.....
Average diameter. ....	.....	.548 in.		.425 in.		.425 in.	

Williamson County, Illinois

1¾	1	18.9	.....	19.0	.....	14.2	.....
1	¾	9.0	27.9	9.2	28.2	7.0	21.2
¾	½	14.4	42.3	15.4	43.6	13.0	34.2
½	⅜	8.5	50.8	9.5	53.1	9.0	43.2
⅜	¼	10.4	61.2	10.6	63.7	11.4	54.6
¼	⅛	15.4	76.6	17.0	80.7	20.2	74.8
⅛	0	23.4	100.0	19.3	100.0	25.2	100.0
Total. ....	.....	100.0	.....	100.0	.....	100.0	.....
Average diameter. ....	.....	.542 in.		.557 in.		.466 in.	

Sangamon County, Illinois

1¾	1	38.8	.....	15.1	.....	15.6	.....
1	¾	7.9	46.7	9.3	24.4	9.1	24.7
¾	½	13.2	59.9	15.6	40.0	15.6	40.3
½	⅜	6.6	66.5	7.7	47.7	9.7	50.0
⅜	¼	7.2	73.7	9.4	57.1	11.5	61.5
¼	⅛	11.2	84.9	17.2	74.3	19.6	81.1
⅛	0	15.1	100.0	25.7	100.0	18.9	100.0
Total. ....	.....	100.0	.....	100.0	.....	100.0	.....
Average diameter. ....	.....	.768 in.		.498 in.		.518 in.	

was nearly doubled in the case of the Vermilion county nut coal, and in the nut coal from Williamson and Sangamon counties there was seven times as much coal below ½ inch in diameter after one and one-half years' storage as there was originally. The average diameter

of the pieces of coal in all three of these lots was about three-fourths as great after storage as before, the average weight being only about four-tenths as great.

The changes in the screenings are not nearly so great as in the nut coal, but even then they are certainly of as much importance as any of the other changes due to weathering. The average diameter of the coal before and after weathering was calculated on the assumption that the diameter of the coal particles through any certain size of hole in the screen was the average of the diameter of that hole and of the one next smaller, i.e., the diameter of coal through the $\frac{1}{2}$ -in. screen and over the $\frac{3}{8}$ -in. screen was considered to be $\frac{7}{16}$ -in. There seems to be no advantage in favor of storage in either open or covered bins so far as the amount of disintegration shown by these experiments is concerned. The disintegration is due to the action of frost; to the opening of small cracks originally started at the time the coal was shot in the mine; and also to the oxidation of pyrite and marcasite, resulting in a large increase in volume, and consequently, a breaking up of the pieces of coal. With lump coal intended for sale or reshipment, this disintegration must result in a large decrease in value. While no sizing tests are available as proof, it seems probable from observation that coal kept absolutely dry, and not subjected even partially to the weather (as was that stored in covered bins), would not break up to the extent shown in these experiments. Probably the ideal way to store coal, so far as disintegration is concerned, would be under water, thus obviating the action of frost entirely. The friability of the coal after storage seems much increased, and any rehandling must result in much greater breakage than it would with freshly mined coal.

V. CHANGE IN WEIGHT

The storage of coal has been thought by some investigators to result in a considerable loss in weight. If the coal heats considerably and fires occur in the storage piles, there is undoubtedly a great loss in weight, but it is still an open question as to how great this change is in storage under fair average conditions. The change in the weight of air-dry or wet coal cannot be considered in this connection. The exact weight of dry coal must be ascertained by some means. The coal must be weighed, and then dried in an oven at some certain temperature for an exact determination of the amount of moisture

in it at the time, as it is not possible to get the coal into such an air-dry condition before and after storage that it will contain exactly the same percentage of moisture each time. The coal in these experiments was weighed, sampled carefully, and the moisture determined at 105° C. The weight of the moisture was then deducted from the weight of the air-dry coal, and the resulting weight of dry coal was used in making all comparisons. The results are given in Tables 3, 4 and 5. The larger samples (Table 3) show a loss of about one and one-half per cent in weight in two cases out of six, the other four show no change within the limits of experimental error, and it is doubtful whether even these two are not chargeable to possible discrepancies in moisture determinations rather than to any actual change in weight. The results of these experiments show only that any change in weight that does occur is very small in amount and is not to be considered unless the coal has heated considerably. Further data along this line are necessary, especially with large samples under actual storage conditions, before any conclusions as to either an increase or decrease in weight would be warranted.

TABLE 3
CHANGE IN WEIGHT OF COAL EXPOSED TO THE AIR

DESCRIPTION	Weight of Coal Dried at 105° C.	Weight of Coal Dried at 105° C.	Change in Weight	
			pounds	per cent
Screenings from	pounds	pounds		
Williamson Co., Ill.	Weighed Dec. 15, '08	Reweighed June 17, '09		
In open box on roof.....	311.8	307.0	-4.8	-1.54
In barrel in building.....	300.7	300.5	-0.2	-.07
Sangamon Co., Ill.	Nov. 27, '08	June 17, '09		
In open box on roof.....	227.7	224.4	-3.3	-1.45
In barrel in building.....	235.8	235.9	+0.1	+.04
Vermilion Co., Ill.	Nov. 11, '08	June 17, '09		
In open box on roof.....	289.0	288.9	-0.1	-.03
In barrel in building.....	284.0	284.9	+0.9	+.32

SIZING TEST ON SCREENINGS VERMILION COUNTY, ILL ORIGINAL SIZES

1 21.3	2 16.4	3 11.1	4 8.5	5 14.8	6 8.9	7 19.0					
EXPOSED BINS ¹											
1 27.4	2 21.0	3 11.8	4 9.3	5 12.9	6 6.3	7 11.3					
COVERED BINS ¹											
1 27.8	2 21.0	3 11.8	4 9.3	5 12.2	6 6.3	7 11.3					
WILLIAMSON COUNTY, ILL ORIGINAL SIZES											
1 23.4	2 15.4	3 10.4	4 8.5	5 14.4	6 9.0	7 18.9					
EXPOSED BINS ¹											
1 19.3	2 17.0	3 10.6	4 9.5	5 15.4	6 9.2	7 19.0					
COVERED BINS ¹											
1 25.2	2 20.2	3 11.4	4 9.0	5 13.0	6 7.0	7 14.2					
SANGAMON COUNTY, ILL ORIGINAL SIZES											
1 15.1	2 11.2	3 7.2	4 6.6	5 13.2	6 7.9	7 38.8					
EXPOSED BINS ¹											
1 25.7	2 17.2	3 9.4	4 7.7	5 15.6	6 9.3	7 15.1					
COVERED BINS ¹											
1 18.9	2 19.6	3 11.5	4 9.7	5 15.6	6 9.1	7 15.6					
PER CENT											
0	10	20	30	40	50	60	70	80	90	100	
SIZES OF COAL - ROUND HOLE SCREEN											
1 0 - $\frac{1}{8}$ "	2 $\frac{1}{8}$ - $\frac{1}{4}$ "		3 $\frac{1}{4}$ - $\frac{3}{8}$ "		4 $\frac{3}{8}$ - $\frac{1}{2}$ "		5 $\frac{1}{2}$ - $\frac{3}{4}$ "		6 $\frac{3}{4}$ - 1"		7 1 - $\frac{13}{16}$ "

¹ AFTER ONE AND ONE-HALF YEARS' STORAGE

Fig. 5

TABLE 4
CHANGE IN WEIGHT OF COAL EXPOSED TO THE AIR

Lab. No.	DESCRIPTION	Weight of Coal Dried at 105° C. grams	Weight of Coal Dried at 105° C. grams	Gain in Weight grams	Gain in Weight per cent
	Screenings	Weighed Feb. 14, '08	Reweighed Nov. 17, '08		
1212	Williamson Co., Ill. . . .	Dry 1331	1348	17	1.28
1213	" " " " . . .	Wet ¹ 1222	1233	11	.90
1214	Sangamon " " " " . . .	Dry 1099	1114	15	1.36
1215	" " " " " " . . .	Wet ¹ 1121	1142	21	1.87
1216	Vermilion " " " " . . .	Dry 1021	1028	7	.69
1217	" " " " " " . . .	Wet ¹ 1056	1061	5	.47
	Nut Coal	Feb. 26, '08	Sept. 16, '08		
1219	Vermilion Co., Ill.	Dry 947	960	13	1.37
1221	Sangamon " " " " " "	" 1196	1222 ²	26	2.17
1223	Williamson " " " " " "	" 1138	1159	21	1.85
1220	Vermilion " " " " " "				
1222	Sangamon " " " " " "	Wet 3130	3147	17	.54
1224	Williamson " " " " " "				

¹ Water evaporated and left coal dry for last month or six weeks. Considerable ferrous sulphate showed in all samples that had been wet, especially in Lab. No. 1215.

² This sample was reweighed Nov. 17, '08, instead of Sept. 16, '08.

TABLE 5
LOSS IN WEIGHT OF AIR-DRY COAL AT VARIOUS TEMPERATURES UP TO 260° C.

Lab. No.	Weight of Sample grams	TOTAL LOSS IN WEIGHT DUE TO HEATING IN AIR				
		1 hour at 105° C. per cent	4 hours at 105° C. per cent	18 hours at 140° C. per cent	14 hours at 260° C. per cent	44 hours at 260° C. per cent
1591 ¹	1	5.05	4.82	2.75	22.92	38.3
1592 ¹	1	5.65	5.45	2.96	25.00	Lost
1591	2	4.18	4.66	3.07	15.92	34.8
1592	2	4.71	5.08	3.36	14.60	34.3
1551	2	2.89	2.76	.22	19.40	31.3
1567	2	2.74	2.86	1.37	9.92	23.9
1569	1	6.23	6.20	3.66	24.55	48.1
1569	2	6.10	6.09	3.61	19.74	48.3
1569	3	5.95	6.18	4.07	22.89	45.2
1569	4	5.86	6.33	4.35	19.96	44.0
1402 ¹	1	17.90	.....	.....	51.10	63.8

¹ Size of coal 60 mesh, all other samples about 10 mesh.

A similar series of experiments (Table 4) was carried out on a small scale in the laboratory with coal of buckwheat size and smaller, both dry and under water. In about eight months every one of these samples showed a positive gain in weight, ranging from $\frac{1}{2}$ to 2 per cent. The coal kept under water showed the smallest average gain. The gain in weight of these samples was probably due to the absorption of oxygen by the coal substance and also to the oxidation of pyrite and marcasite. The gain in weight of bituminous coal upon heating for a short time at a moderate temperature is a phenomenon which has often been noted by chemists working with this substance. In this laboratory a number of air-dry samples were heated to various temperatures from 105° to 260° C. The figures representing the amount of moisture in the coal are given in the column headed "1 hour at 105° C.," Table 5. The same coals heated for four hours at the same temperature show changes in weight in both directions. The first two samples of finely pulverized coal both increased in weight. The 10-mesh samples in one and two-gram lots changed very little, three gaining and three losing in weight. The four portions of sample No. 1569 show the result of increasing the size of the sample without increasing in the same proportion the surface exposed to the air. The larger portions show a greater loss in weight because they do not have the opportunity to absorb so much oxygen on account of the smaller surface exposed. After 18 hours at 140° C., the losses are all smaller than enough to cover the amount of moisture present, thus indicating a gain in weight due to oxidation. The same relative changes in the four portions of sample No. 1569 are still evident. Heating at 260° C., however, causes a striking loss in weight due to the very rapid oxidation at that temperature which is approaching closely the ignition temperature of the coal. In fact, any quantity of coal of more than 100 grams, of the size used in these experiments, would be very apt to ignite if heated to 260° C.¹

Sampling.—The six cars of coal before mentioned were all inspected at the mine and sampled as they were loaded, to avoid any unknown changes while the coal was in transit. About four hundred pounds was taken at intervals with a scoop from the stream of coal as it comes from the chute, and this sample reduced by quartering to about two pounds, which was sent to the laboratory for immediate analysis. The next series of samples was taken about one week later

¹Eng. Exp. Sta., U. of I., Bul. 24, S. W. Parr and C. K. Francis, June, 1908.

when the coal was being hauled by wagon from the cars to the storage bins. Occasional shovelfuls were taken as the wagons unloaded, until a sample of about three or four hundred pounds was obtained. This was handled as before by alternate crushings and quarterings until only two pounds remained. At the laboratory this sample after air-drying was crushed to $\frac{1}{8}$ inch and smaller, and all further quartering was done with a riffle sampler. When the coal was once in place in the bins, it was thought best not to shovel it over or rehandle it in any way, as any extra handling would change the conditions from those of actual storage and would of course modify any results from sizing tests. To avoid this rehandling, a sampler was designed that would take cores through the whole thickness of the pile without disturbing any of the coal except that taken out as a sample. Ordinarily six cores, seven inches in diameter, were taken from a bin for a sample. This number of holes gave a sample of about 250 to 400 pounds, depending on the depth of the coal in any particular bin. The sampler itself (Fig. 4) is made up of two parts. One is a casing of spiral riveted pipe fitted with a notched shoe to overturn the larger pieces of coal that may be struck as it is forced into the pile. At the top it is protected by a stiffening ring to prevent battering of the pipe. The ring has 1-in. holes in opposite sides to admit the end of a bar or a small piece of pipe to be used as a handle to turn the large pipe, which will usually sink of its own weight, if rotated. This pipe serves only to prevent the coal from caving into the hole. The main part of the sampler is somewhat like a post-hole digger, except that it is fitted with a shutter at the bottom to retain the coal after being filled. It is used to remove the coal from the larger pipe as it is sunk. Casing and sampler are shown in Fig. 6.

VI. CHANGE IN CALORIFIC VALUE

The main part of the present investigation has been devoted to following the changes in calorific value of the actual coal substance. It is impossible to sample any lot of coal exactly as regards ash and sulphur, and for that reason it was found necessary to refer all B. t. u. determinations to the actual coal basis¹ for the sake of comparison. For this purpose the following formula was used.

$$\frac{\text{B. t. u. as determined} - 5000 \times \text{Weight of Sulphur}}{1.00 - (\text{Moisture} + 1.08 \times \text{Ash} + 22/40 \times \text{Sulphur})}$$

¹Bul. No. 37, Eng. Exp. Sta., 1909. S. W. Parr and W. F. Wheeler.

For the benefit of anyone who has not a copy of Bulletin No. 37 at hand, a brief explanation of some of the terms used in the formula follows:

"5000 $\times$ Weight of Sulphur" in pounds per pound of coal represents the heating value of the sulphur in B. t. u. This is deducted from the heating value of the coal given by the calorimeter in order to overcome any variation in the amount of sulphur present in the several coal samples. For purposes of comparison, it is found advisable to consider the sulphur as being extraneous matter and not as part of the coal substance. The term "1.08 $\times$ Ash" represents the mineral matter of the coal that remains after burning completely, and also an additional eight per cent for the water and carbon dioxide that were not part of the coal, but were chemically combined with the mineral matter of the ash and thus took the place of an equal weight of actual coal. The last term "22/40 $\times$ Sulphur" represents the sulphur corrected for the oxygen that replaces it in the ash. When the coal is burned, any sulphur that was combined with iron as pyrite, FeS_2 , is replaced by oxygen, leaving Fe_2O_3 in ash. This exchange results in a loss in weight of only $\frac{5}{8}$ the amount of sulphur burned. Since part of the sulphur is not combined in the form of pyrites, but is in a form which is non-combustible and may remain in the ash, the fraction 22/40 is taken instead of 25/40 as being more nearly the figure which would properly be applied. The denominator, taken as a whole, gives the weight of actual coal in a unit weight of coal as analyzed."

It was found that coal samples, even when kept sealed in glass jars for a few months, change appreciably in calorific value.¹ To avoid any such changes, the analyses and calorimetric determinations were all made not later in any case than ten days after sampling the coal. The Mahler-Atwater bomb calorimeter with platinum lining using compressed oxygen was used for all calorimeter tests. The calorimeter room is shown in Fig. 7.

The change in calorific value of the coal was found to be most rapid during the first few weeks after mining, but it was found to continue at a decreasing rate for more than a year certainly, and probably it continues indefinitely. The greater losses in calorific value occur in the smaller sizes of coal, the screenings in practically every instance suffering more of a loss than the nut coal. The greatest loss in any instance was found in the Sangamon county screenings.

¹Bul. No. 17, Eng. Exp. Sta. S. W. Parr and W. F. Wheeler. J. Am. Chem. Soc., Vol. 30, p. 1027

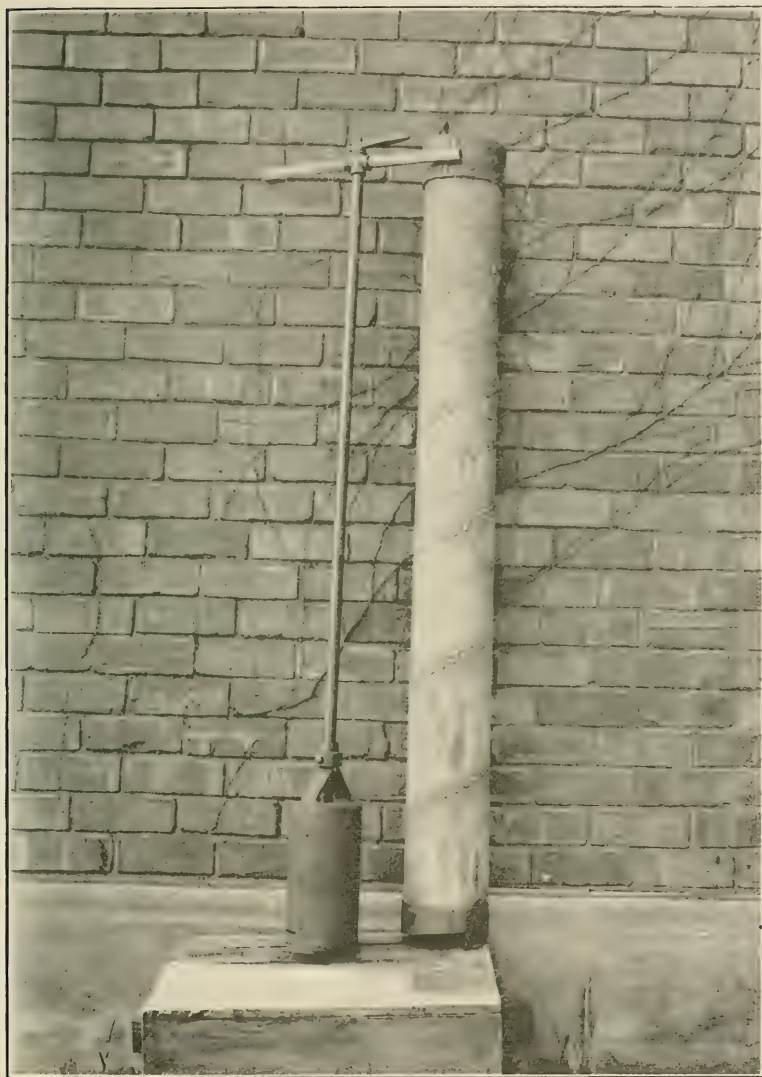


Fig. 6

and that was but 5.14 per cent. The average losses for all sizes and both methods of storage, in open and covered bins, for one year is practically 3 per cent. Tables 6 to 12 inclusive and Fig. 8 to 15 inclusive show the losses for coals from different seams and different storage



Fig. 7

conditions. Table 12 is made up of average values from the six preceding tables, and it seems reasonable to suppose that it shows about what may be expected of Illinois coals when stored. The loss for one year was found to be only 2.76 per cent when exposed to the weather, against 3.14 per cent when in covered bins, and 1.49 per cent when stored under water. Nearly one-third of the loss took place during shipment, except in the case of the coal stored under water, when more than one-half of the loss occurred in the first week. None of the losses in calorific value thus far noted are great enough to warrant any changes in present storage methods, but there is a possibility that protection from spontaneously ignited fires and lessened breakage may make storage under water advisable in many instances.

The Christian county coal heated to a considerable extent and

TABLE 6
VERMILION COUNTY, ILLINOIS, NUT COAL

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal ¹	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1031	Same day as mined.	10.55	4.25	12991	14814	.....	.....
1081	7 days after mining.	13.98	2.65	12412	14716	98	.66
1240	2 months " "	14.21	2.47	12265	14577	237	1.60
1656	6 " " "	13.53	2.10	12396	14575	239	1.61
2088	1 year " "	13.62	2.82	12282	14498	316	2.13
Stored in Covered Bins							
1031	Same day as mined.	10.55	4.25	12991	14814	...	.....
1081	7 days after mining.	13.98	2.65	12412	14716	98	.66
1249	2 months " "	13.08	2.13	12475	14604	210	1.42
1662	6 " " "	11.76	2.14	12571	14472	342	2.31
2094	1 year " "	13.52	2.72	12220	14403	411	2.77
Stored under Water							
1031	Same day as mined.	10.55	4.25	12891	14814	...	.....
1081	" " " submerged.	13.98	2.65	12412	14716	98	.66
1647	6 months after mining.	15.37	3.34	12013	14524	290	1.96
2100	1 year " "	13.85	3.81	12231	14517	297	2.00

¹ For meaning of actual or unit coal, see formula on page 23.

caught fire several times, the fire in each case being extinguished by a large quantity of water. Even in this case the loss was not of a very serious nature, being less than 3 per cent, only a little higher than would have occurred if the coal had not heated at all.

The coal from Fulton county showed a small decrease, only 0.7 per cent, in calorific value, when compared with coal two weeks after mining. If a fresher sample of coal had been available for determining the original B. t. u. value, the loss shown would have been at least double that found. The analyses of the coals from Christian and Fulton counties are found in Table 13.

For some unknown reason, the losses in calorific value shown in Table 14 for the second lot of Vermilion county screenings after about two and one-half years' storage are less than might be expected considering the losses shown by the other coal from the same county.

TABLE 7
WILLIAMSON COUNTY, ILLINOIS, NUT COAL

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1090 1091	Same day as mined.....	13.98	3.73	12499	14859	...	....
1098	7 days after mining.....	14.90	3.02	12341	14821	38	.26
1246	2 months " ".....	14.32	4.12	12409	14835	24	.16
1657	6 " " ".....	13.81	3.45	12455	14765	95	.64
2090	1 year " ".....	11.88	2.73	12759	14734	125	.84
Stored in Covered Bins							
1090 1091	Same day as mined.....	13.98	3.73	12499	14859	...	....
1098	7 days after mining.....	14.90	3.02	12341	14821	38	.26
1247	2 months " ".....	14.08	3.84	12378	14739	120	.81
1663	6 months " ".....	13.06	3.60	12469	14644	215	1.45
2096	1 year " ".....	13.24	3.20	12428	14616	243	1.64
Stored under Water							
1090 1091	Same day as mined.....	13.98	3.73	12499	14859	...	....
1098	" " " submerged.....	14.90	3.02	12341	14821	38	.26
1648	6 months after mining.....	15.65	3.12	12097	14673	186	1.25
2102	1 year " ".....	14.87	3.42	12251	14721	138	.93

(See Tables 6 and 9.) The changes for the second year are shown to be only about one-half those for the first year. However, in this case, the coal seems to have reached a stage where the loss occurs at a uniform rate of about 0.1 per cent per month where the coal is stored without protection from the weather.

About fifteen months after mining, one sample was taken from this lot of coal to represent the whole pile and another to represent the outside six inches of the pile, with the expectation that the surface layers would show greater losses than the whole mass. The calorific values of the two samples, however, varied by only a few B. t. u., not a difference greater than the limit of accuracy of the determination.

Coal that will weather in the open air ought to weather to almost

TABLE 8
SANGAMON COUNTY, ILLINOIS, NUT COAL

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1078	Same day as mined.....	17.87	5.75	11741	14773	.....	....
1084	7 days after mining.....	16.63	5.10	11800	14571	202	1.37
1248	2 months “ “	17.45	4.66	11626	14497	276	1.87
1658	6 “ “ “	16.03	4.91	11798	14444	329	2.23
2086	1 year “ “	14.97	4.68	11860	14307	466	3.15
Stored in Covered Bins							
1078	Same day as mined.....	17.87	5.75	11741	14773	....	.....
1084	7 days after mining.....	16.63	5.10	11800	14571	202	1.37
1250A	2 months “ “	16.08	5.03	11912	14600	173	1.17
1250B	2 “ “ “	17.57	5.01	11626	14535	238	1.61
1664	6 “ “ “	16.30	4.52	11682	14336	437	2.96
2092	1 year “ “	15.99	4.65	11589	14165	608	4.12
Stored under Water							
1078	Same day as mined.....	17.87	5.75	11741	14773	...	....
1084	“ “ “ submerged.....	16.63	5.10	11800	14571	202	1.37
1649	6 months after mining.....	15.90	4.21	11854	14461	322	2.18
2098	1 year “ “ “	15.95	5.11	11851	14503	270	1.83

as great an extent when exposed in the mine, but samples taken from old pillars in two Illinois mines, after an exposure for about twenty-five years, show less than three per cent loss in either case. The coal showed no shrinkage or change in physical appearance in either of these pillars after about one-half inch of dirty coal was removed from the surface. The analyses of these samples of old coal and of a sample from an outcrop in Peoria county are presented in Table 15. This outcrop coal represents the greatest deterioration that has so far come to our knowledge. In fact, the sample from the outcrop shows almost a complete change in the character of the coal. It has every physical appearance of a brown lignite, while the unaltered coal from the same seam was a fair grade of bituminous coal not different from other Illinois coals. This change appears to be in the wrong direction to agree with most of the accepted theories of coal formation. Most of the writers on coal formation think that our coal deposits

TABLE 9
VERMILION COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1032	Same day as mined.	17.88	2.35	11937	14888	...	....
1080	7 days after mining.	13.98	2.87	12414	14726	162	1.09
1082	7 "						

have gone through the various stages from peat to anthracite. In this case the sulphur is almost free from the coal, supposedly by oxidation and leaching. The thickness of the No. 5 coal seam is remarkably uniform in this locality, and the thickness of the outcrop coal is not different from the thickness of the seam in other places near-by where the coal is unchanged. Thus, no evidence is offered that the seam at this place had suffered any very great shrinkage.

The coal stored by the Commonwealth Edison Company of Chicago was sampled after fifteen months' storage and losses of only about one per cent were found, although the final samples were taken from the surface of the piles. (See analytical results, Table 16.) The

TABLE 10
WILLIAMSON COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1089	Same day as mined.....	14.13	3.17	12426	14782	...	....
1099	7 days after mining.....	14.37	3.34	12287	14666	116	.78
1244	2 months “ “.....	15.66	2.67	12133	14701	81	.55
1654	6 “ “ “.....	13.76	2.84	12342	14597	185	1.25
2091	1 year “ “.....	13.77	2.75	12328	14579	203	1.37
Stored in Covered Bins							
1089	Same day as mined.....	14.13	3.17	12426	14782	...	....
1099	7 days after mining.....	14.37	3.34	12287	14666	116	.78
1245	2 months “ “.....	12.62	2.98	12608	14705	77	.52
1660	6 “ “ “.....	13.60	3.03	12372	14610	172	1.16
2097	1 year “ “.....	13.43	2.72	12385	14582	200	1.35
Stored under Water							
1089	Same day as mined.....	14.13	3.17	12426	14782	...	....
1099	“ “ “ submerged.....	14.37	3.34	12287	14666	116	.78
1645	6 months after mining.....	14.38	3.54	12262	14645	137	.93
2103	1 year “ “.....	13.60	2.97	12447	14698	84	.57

coal in these large piles seemed to have broken up very slightly, and no objectionable heating was noticed.

VII. CONCLUSIONS

Coal of the type found in Illinois and neighboring states is not affected seriously during storage when only the changes in weight and losses in heating power are considered. The changes in weight may be either gains or losses of probably never over two per cent in a period of one year. The heating value decreases most rapidly during the first week after mining and continues to decrease more and more slowly for an indefinite time. In the coals that have been tested, one per cent is about the average loss for the first week and three to three and one-half per cent would cover the losses for a year,

TABLE 11
SANGAMON COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u		B. t. u.	per cent
Stored in Exposed Bins							
1079	Same day as mined.	17.13	4.92	11752	14604	...	....
1085	7 days after mining.	17.04	4.47	11684	14481	123	.84
1242	2 months " "	17.22	5.00	11645	14488	116	.79
1655	6 " " "	17.02	4.54	11526	14281	323	2.21
2087	1 year " "	17.25	4.54	11153	13853	751	5.14
Stored in Covered Bins							
1079	Same day as mined.	17.13	4.92	11752	14604	...	....
1085	7 days after mining.	17.04	4.47	11684	14481	123	.84
1243	2 months " "	18.33	4.70	11414	14404	200	1.37
1661	6 " " "	17.30	4.67	11466	14263	341	2.33
2093	1 year " "	17.06	4.73	11248	13944	660	4.52
Stored under Water							
1079	Same day as mined.	17.13	4.92	11752	14604	...	....
1085	" " " submerged.	17.04	4.47	11684	14481	123	.84
1646	6 months after mining.	19.86	5.60	11127	14372	232	1.59
2099	1 year " " "	18.27	4.81	11479	14478	126	.86

although in some instances the loss was found to be as high as five per cent in a year.

The losses due to disintegration of the coal and to spontaneous ignition seem to be of far greater importance than any changes in weight and heating value, although they cannot be expressed in figures for comparison. The storage of coal of a size larger than is to be used would overcome part of this objection to storage, as the coal could be crushed to the most advantageous size just before firing. The larger sizes of coal are also much less liable to take fire spontaneously. Storage under water will prevent disintegration of the coal to a very large extent, and it will absolutely prevent any fire losses. Aside from these advantages in favor of storing coal under water, there seems to be very little to be said in favor of any particular method of storing coal.

TABLE 12
AVERAGE VALUES FROM SIX PRECEDING TABLES

	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal ¹	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
	Stored in Exposed Bins						
....	Same day as mined.	15.26	4.03	12224	14787	...	....
....	7 days after mining.	15.13	3.53	12164	14666	121	.82
....	2 months " "	15.68	3.61	12024	14606	181	1.22
....	6 " " "	14.96	3.36	12081	14525	262	1.77
....	1 year " "	14.33	3.29	12065	14379	408	2.76
	Stored in Covered Bins						
....	Same day as mined.	15.26	4.03	12224	14787	...	....
....	7 days after mining.	15.13	3.53	12164	14666	121	.82
....	2 months " "	15.07	3.53	12128	14605	182	1.22
....	6 " " "	14.42	3.37	12105	14453	334	2.26
....	1 year " "	14.77	3.57	11945	14323	464	3.14
	Stored under Water						
....	Same day as mined.	15.26	4.03	12224	14787	...	....
....	" " " submerged.	15.13	3.53	12164	14666	121	.82
....	6 months after mining.	15.84	3.69	11937	14532	255	1.73
....	1 year " "	15.02	3.81	12090	14567	220	1.49

TABLE 13
CHRISTIAN COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
....	When stored (about 2 weeks after mining).....	19.20	5.04	11325	14475	...	....
1422	Five months in exposed pile of 500 tons (had heated badly).....	16.68	4.43	11425	14083	392	2.71
FULTON COUNTY, ILLINOIS, SCREENINGS.							
1405	Two weeks after mining....	20.97	3.42	11114	14500	....	....
1406	Six months in exposed pile three feet deep.....	21.12	3.17	11021	14398	1.02	.70

¹ For meaning of actual or unit coal, see formula on page 23.

TABLE 14

VERMILION COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal ¹	Decrease	
		Asb	Sulphur	B. t. u.		B. t. u.	per cent
	In Exposed Pile						
....	When mined.....	....	....	....	14850 ²	...	....
144	About two weeks after min-						
147	ing.....	19.11	1.96	11561	14644	206	1.39
973	15 months after mining.....	19.54	2.20	11368	14491	359	.42
1627	22 " " " ".....	20.61	1.88	11134	14392	458	3.08
2104	28 " " " ".....	21.70	1.83	10901	14307	543	3.66
	Stored under Water						
....	When mined.....	....	....	....	14850	...	....
975	15 months after submerging.	15.90	2.29	12154	14761	89	.60
2105 ³	28 " " " ".....	17.75	1.97	11686	14531	319	2.15

¹ Calorific value taken from other analyses of fresh coal from same mine and neighboring mines.

² Coal was not completely covered with water for last two months.

³ For meaning of actual or unit coal, see formula on page 23.

TABLE 15

ANALYSES OF PILLAR-COAL AND OUTCROP COAL COMPARED WITH FRESH COAL

Lab. No.	Description	Total Moisture	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
			Ash	Sulphur	B. t. u.		B. t. u.	per cent
ST. CLAIR COUNTY, ILLINOIS								
991	Fresh Coal.....	9.76	15.80	4.76	12202	14896	...	....
992	Pi lar-coal exposed 22 years.....	10.18	16.21	5.01	11797	14482	414	2.78
GALLATIN COUNTY, ILLINOIS								
1092	Fresh coal.....	4.47	10.85	3.72	13235	15133	...	....
1093	Pillar-coal exposed 27 years.....	4.76	13.84	3.84	12514	14857	276	1.82
PEORIA COUNTY, ILLINOIS								
1407	Fresh coal.....	13.86	16.25	3.91	12044	14757	...	....
1402	Outerop coal,slight- ly covered with soil.....	29.81	16.86	.85	9257	11331	3426	23.21

TABLE 16
COMMONWEALTH EDISON COMPANY, CHICAGO
Stored Coal

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal ¹	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u	per cent
	FRANKLIN CO., ILLINOIS						
	Nut Coal						
1337 } 1414 }	April, 1908.	10.16	1.81	13021	14688	....	....
2619	July 14, 1909.	10.44	2.15	12924	14642	46	.31
	WILLIAMSON COUNTY AND FRANKLIN COUNTY, ILLINOIS						
	Egg Coal						
1335 } 1415 }	April, 1908.	10.97	2.35	12909	14728	...	....
2620	July 14, 1909.	11.49	1.84	12697	14559	169	1.15
	WILLIAMSON Co., ILLINOIS						
	No. 1 Washed Nut						
1336 } 1416 }	April, 1908.	9.21	1.82	13205	14726	...	....
2618	July 14, 1909.	9.43	1.72	13008	14540	186	1.26

¹ For meaning of actual or unit coal, see formula, p. 23.

VERMILION COUNTY, ILLINOIS

NUT COAL

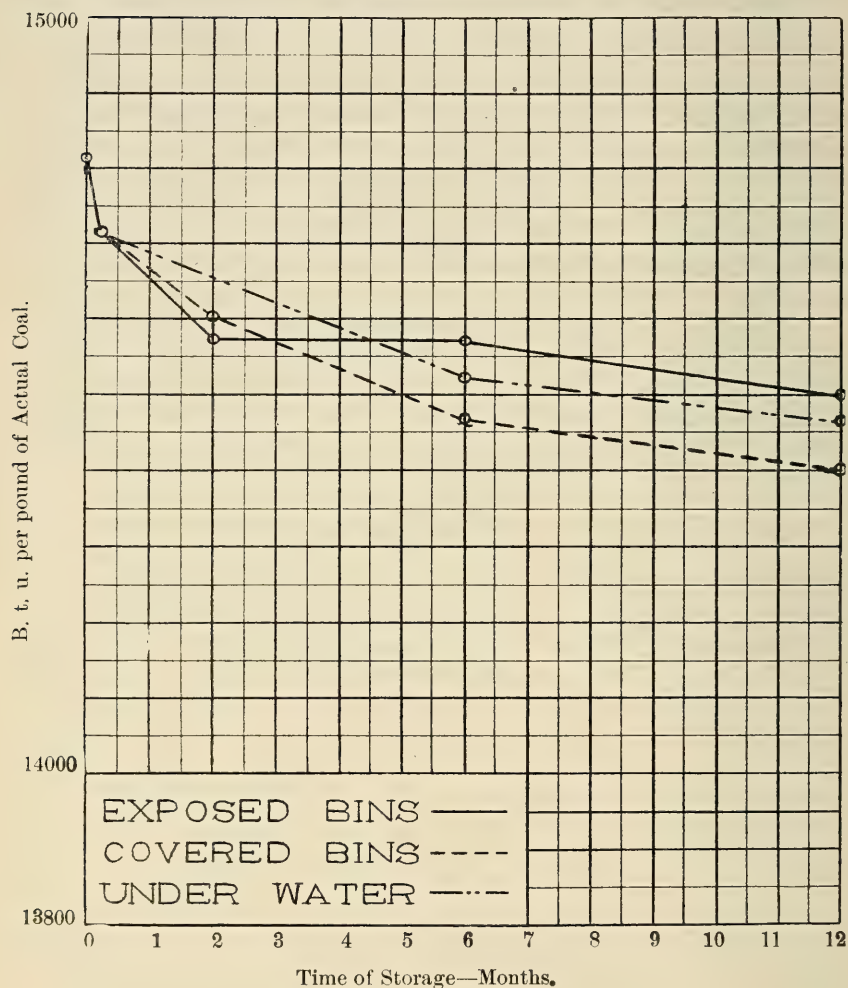


Fig. 8

WILLIAMSON COUNTY, ILLINOIS

NUT COAL

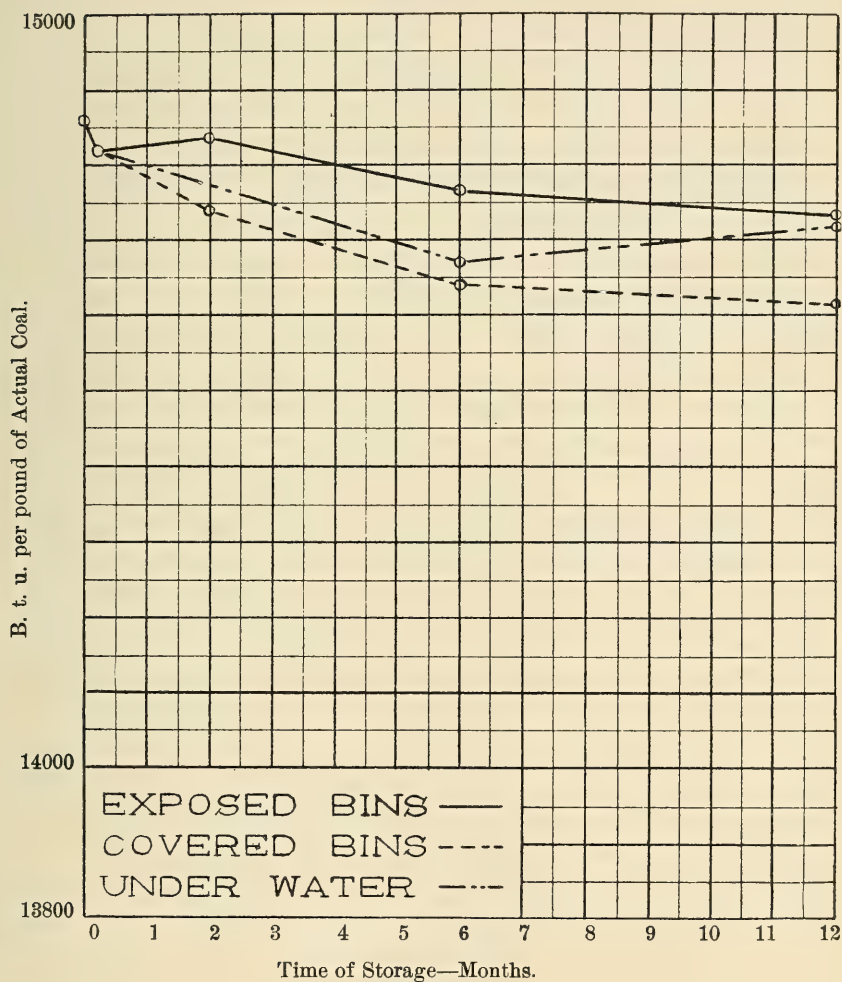


Fig. 9

SANGAMON COUNTY, ILLINOIS
NUT COAL

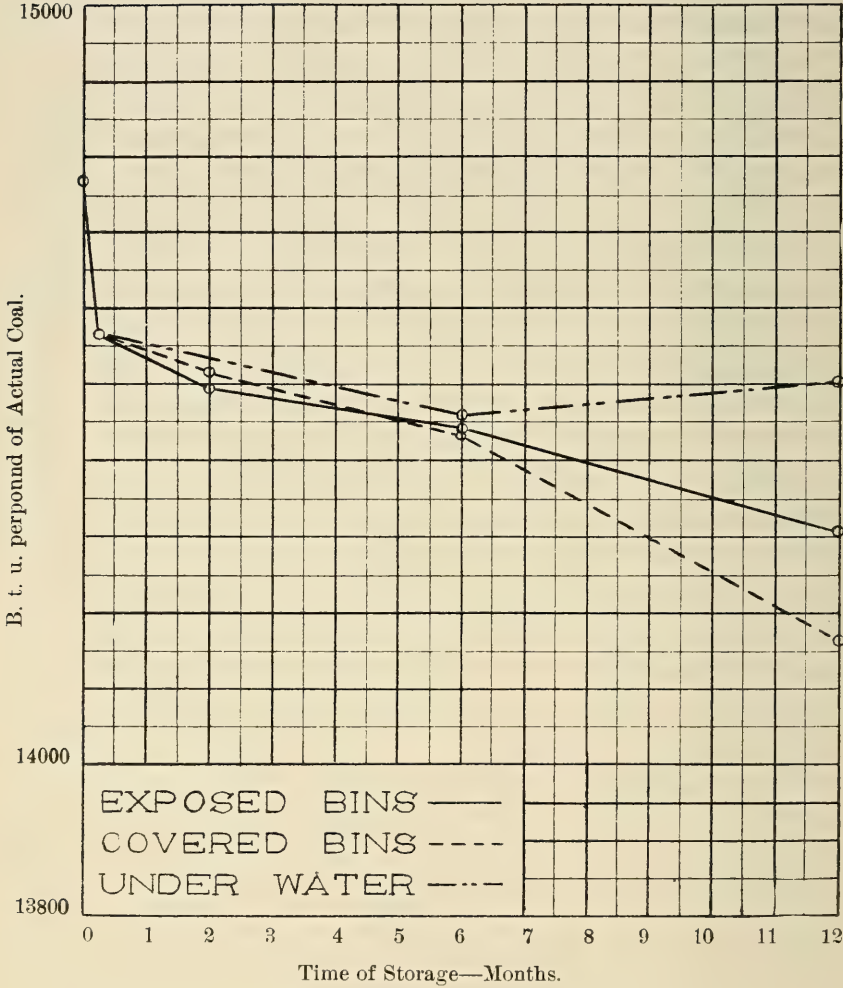


Fig. 10

VERMILION COUNTY, ILLINOIS

SCREENINGS

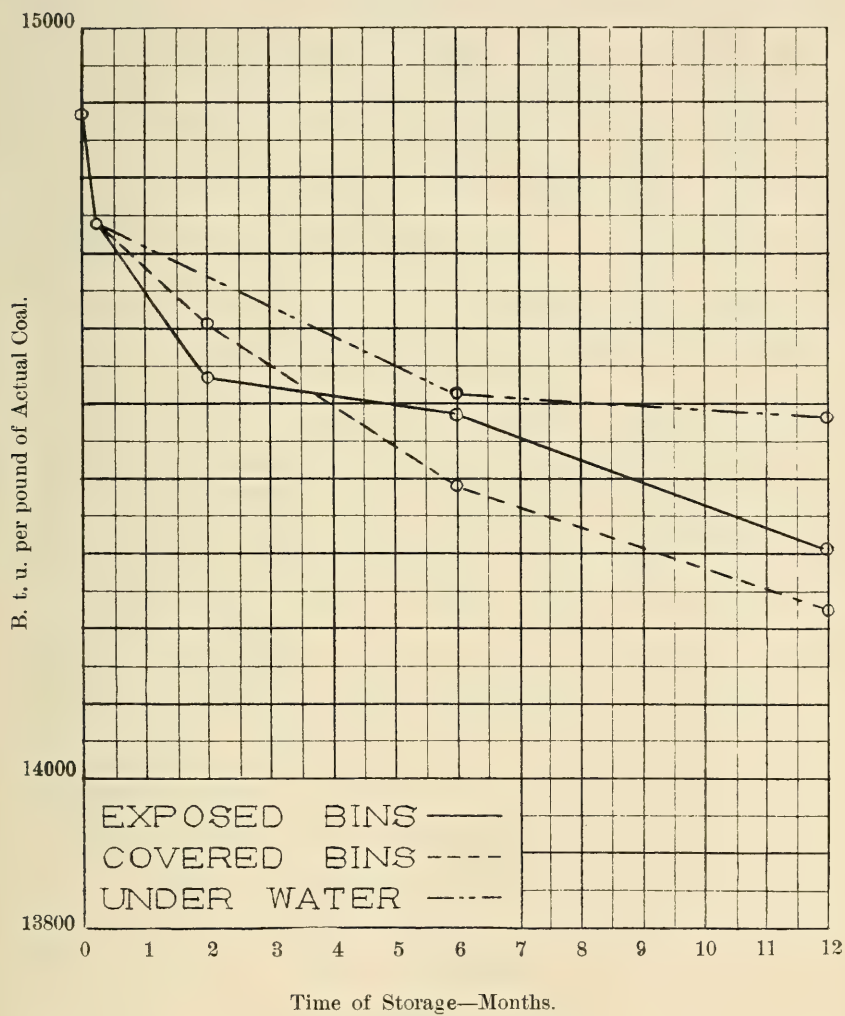


Fig. 11

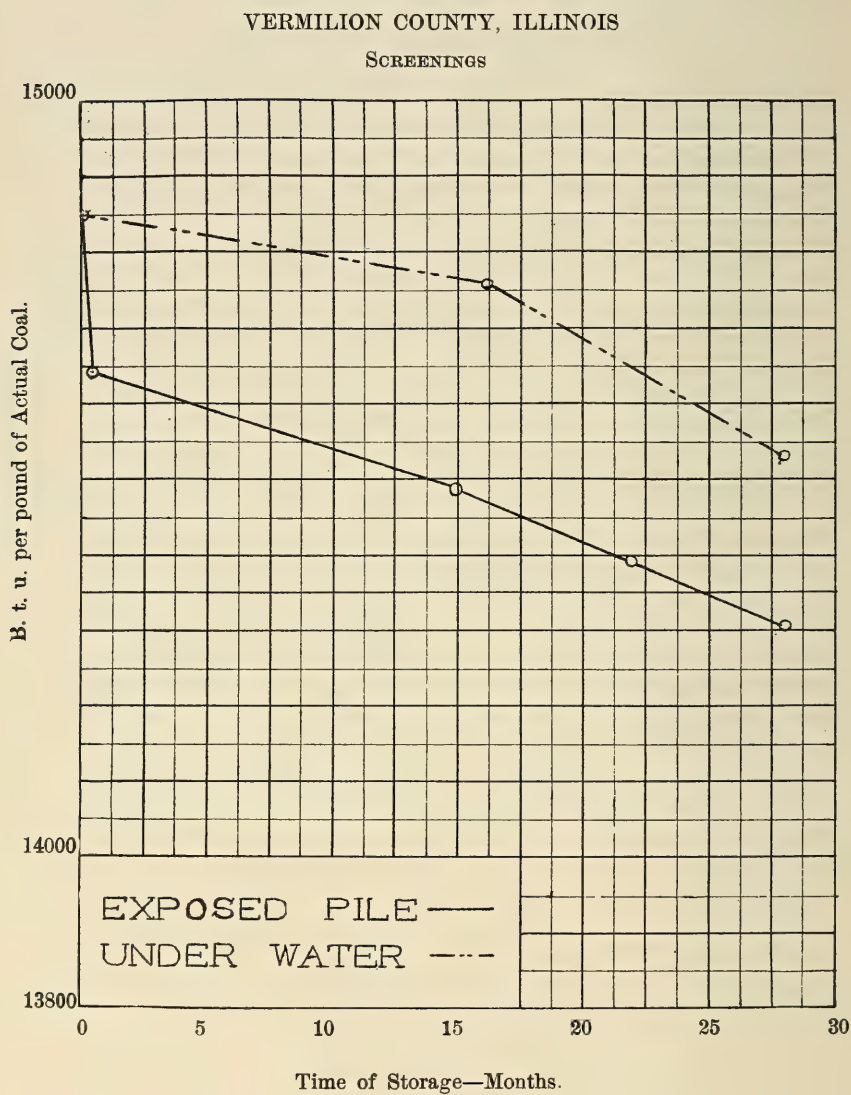


Fig. 12

WILLIAMSON COUNTY, ILLINOIS

SCREENINGS

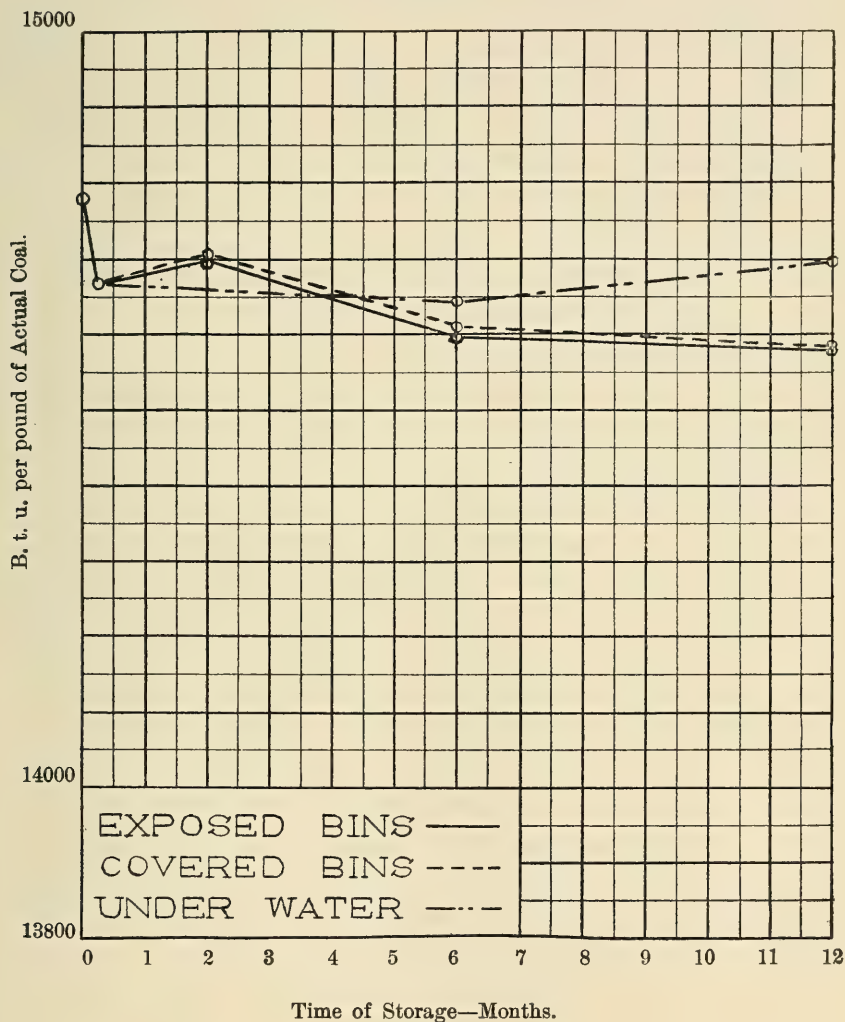


Fig. 13

SANGAMON COUNTY, ILLINOIS

SCREENINGS

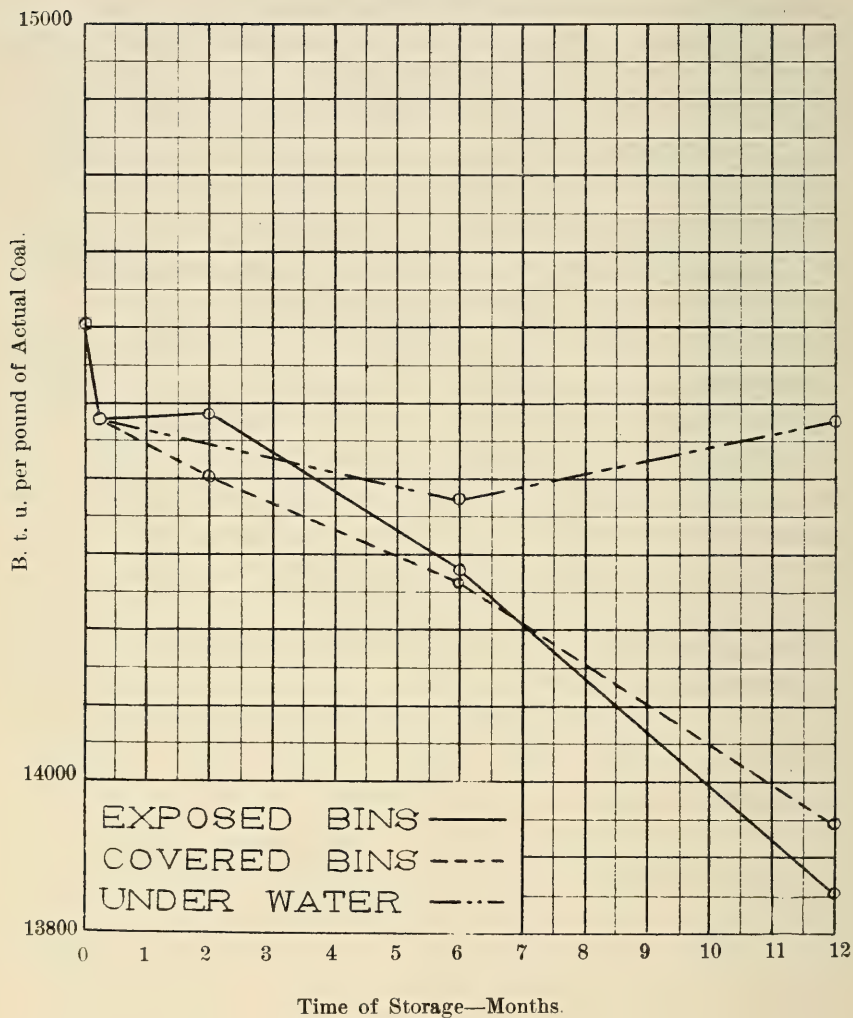


Fig. 14

AVERAGE VALUES FROM THE SIX PRECEDING TABLES.

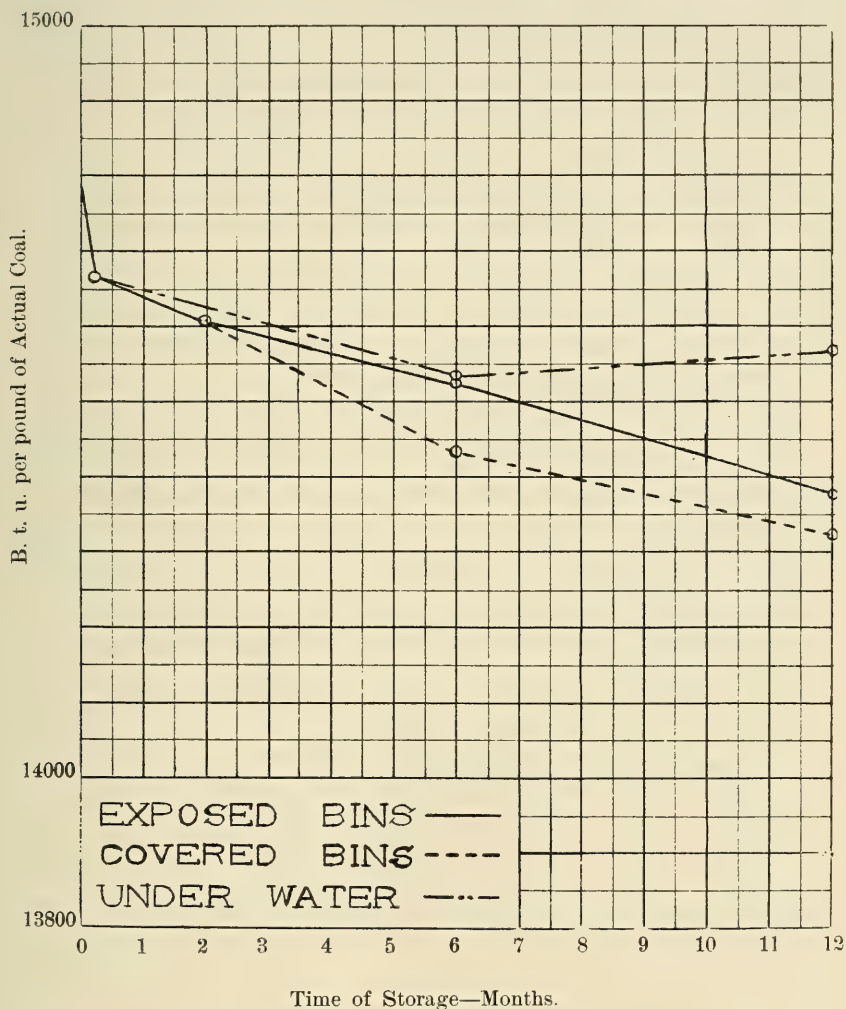


Fig. 15

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

- Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print.*)
- Circular No. 1.* High-Speed Tool Steels, by L. P. Breckenridge. 1905. (*Out of print.*)
- Bulletin No. 2.* Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. (*Out of print.*)
- Circular No. 2.* Drainage of Earth Roads, by Ira O. Baker. 1906. (*Out of print.*)
- Circular No. 3.* Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907, by L. P. Breckenridge and Paul Diserens. 1909.)
- Bulletin No. 3.* The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (*Out of print.*)
- Bulletin No. 4.* Tests of Reinforced Concrete Beams. Series of 1905, by Arthur N. Talbot. 1906.
- Bulletin No. 5.* Resistance of Tubes to Collapse, by Albert P. Carman. 1906. (*Out of print.*)
- Bulletin No. 6.* Holding Power of Railroad Spikes, by Roy I. Webber. 1906. (*Out of print.*)
- Bulletin No. 7.* Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906. (*Out of print.*)
- Bulletin No. 8.* Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906. (*Out of print.*)
- Bulletin No. 9.* An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.
- Bulletin No. 10.* Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print.*)
- Bulletin No. 11.* The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907. (*Out of print.*)
- Bulletin No. 12.* Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print.*)
- Bulletin No. 13.* An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.
- Bulletin No. 14.* Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907. (*Out of print.*)
- Bulletin No. 15.* How to Burn Illinois Coal without Smoke, by L. P. Breckenridge. 1908.
- Bulletin No. 16.* A Study of Roof Trusses, by N. Clifford Ricker. 1908.
- Bulletin No. 17.* The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1908. (*Out of print.*)
- Bulletin No. 18.* The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1908.
- Bulletin No. 19.* Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908.
- Bulletin No. 20.* Tests of Concrete and Reinforced Concrete Columns, Series of 1907, by Arthur N. Talbot. 1908.
- Bulletin No. 21.* Tests of a Liquid Air Plant, by C. S. Hudson and C. M. Garland. 1908.
- Bulletin No. 22.* Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. 1908.
- Bulletin No. 23.* Voids, Settlement and Weight of Crushed Stone, by Ira O. Baker. 1908.
- Bulletin No. 24.* The Modification of Illinois Coal by Low Temperature Distillation, by S. W. Parr and C. K. Francis. 1908.
- Bulletin No. 25.* Lighting Country Homes by Private Electric Plants, by T. H. Amrine. 1908.
- Bulletin No. 26.* High Steam-Pressures in Locomotive Service. A Review of a Report to the Carnegie Institution of Washington. By W. F. M. Goss. 1908.
- Bulletin No. 27.* Tests of Brick Columns and Terra Cotta Block Columns, by Arthur N. Talbot and Duff A. Abrams. 1909.
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- Bulletin No. 37.* Unit Coal and the Composition of Coal Ash, by S. W. Parr and W. F. Wheeler. 1909.
- Bulletin No. 38.* The Weathering of Coal, Series of 1909, by S. W. Parr and W. F. Wheeler. 1909.

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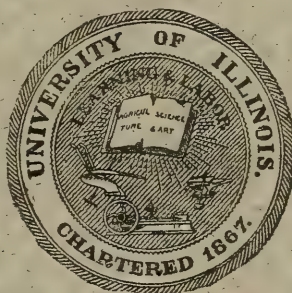
[Entered Feb. 14, 1902, at Urbana, Ill., as second-class matter under Act of Congress July 16, 1894]

BULLETIN NO. 39

TESTS OF WASHED GRADES OF ILLINOIS COAL

BY

C. S. McGOVNEY



UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

URBANA, ILLINOIS
PUBLISHED BY THE UNIVERSITY



THE Engineering Experiment Station was established by action of the Board of Trustees, December 8, 1903. It is the purpose of the Station to carry on investigations along various lines of engineering and to study problems of importance to professional engineers and to the manufacturing, railway, mining, constructional, and industrial interests of the State.

The control of the Engineering Experiment Station is vested in the heads of the several departments of the College of Engineering. These constitute the Station Staff, and with the Director, determine the character of the investigations to be undertaken. The work is carried on under the supervision of the Staff; sometimes by a research fellow as graduate work, sometimes by a member of the instructional force of the College of Engineering, but more frequently by an investigator belonging to the Station corps.

The results of these investigations are published in the form of bulletins, which record mostly the experiments of the Station's own staff of investigators. There will also be issued from time to time in the form of circulars, compilations giving the results of the experiments of engineers, industrial works, technical institutions, and governmental testing departments.

The volume and number at the top of the title page of the cover are merely arbitrary numbers and refer to the general publications of the University of Illinois; *above the title is given the number of the Engineering Experiment Station bulletin or circular, which should be used in referring to these publications.*

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 39

AUGUST 1909

TESTS OF WASHED GRADES OF ILLINOIS COAL

BY C. S. MCGOVNEY, FORMERLY ASSISTANT IN THE ENGINEERING
EXPERIMENT STATION, IN CHARGE OF FUEL TESTS

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A NOTE OF ACKNOWLEDGMENT

A few years ago, Professor L. P. Breckenridge, while Director of the Engineering Experiment Station, outlined an elaborate series of fuel tests to be undertaken by the Station. In the development of his plans, he invited the cooperation of several distinguished engineers, and to them special acknowledgment is made for many helpful suggestions and criticisms. Those who contributed to the work constituted a Fuel Test Conference Committee, the members of which were Messrs. W. L. Abbott, representing the Board of Trustees, University of Illinois; H. Foster Bain, representing the State Geological Survey; A. Bement, representing the Western Society of Engineers; E. H. Cheney, representing the Building Managers' Association of Chicago; F. H. Clark, representing the Western Railway Club; A. Mueller, representing the Illinois Manufacturers' Association; Carl Scholz, representing the Illinois Coal Operators' Association; and A. V. Schroeder, representing the State Electric Light Association. Dr. Bain also gave attention to the selection of the various samples of coal tested. The necessary chemical work was carried on under the direction of Professor S. W. Parr. Material assistance was also rendered by the Technologic Branch of the United States Geological Survey, as represented by its chief, Mr. J. A. Holmes. The author, Mr. C. S. McGovney, acting under the general direction of Professor Breckenridge, has been responsible for the immediate charge and direct supervision of the work.

The work of testing, which proceeded under these plans, has been advanced by methods involving the utmost care, and with results, which, in part, are presented by this bulletin. While the present publication is complete in the sense that it constitutes a final presentation of data covering a definite field, it is to be accepted as a report of a particular phase of the work, rather than as a complete definition of the plans of the Fuel Test Committee.

W. F. M. G.

Engineering Experiment Station
University of Illinois
February, 1910

I. INTRODUCTION

1. During the years 1906 and 1907, the Engineering Experiment Station conducted a series of steam boiler trials as part of an investigation of the fuel value of certain Illinois coals. The results of these tests and a discussion of their significance will be found in the following pages. The data apply specifically to a Heine 210 horse-power water-tube boiler, set singly, and served with a 54-in. Green traveling link grate operated under induced draft pressure. A description of this plant will be found in Appendix I.

2. *Object of the Tests.*—This study has for its primary object the comparison of various grades of Illinois washed coal. With this in view, the tests were planned to facilitate comparisons with respect to the following points:

(a) Determination of the relation of grade of coal to the economy of evaporation and horse-power obtainable.

(b) Determination of the effect of varying rates of combustion upon the economy with various grades.

(c) Effect of different depths of fuel beds.

(d) Study of the fuel bed, draft and draft pressure requirements for each grade.

3. *Development of Methods.*—In experimental furnace work, the difficulty of controlling variables and measuring quantities depends in some degree upon the peculiarities of the furnace and the object of the experimental work. In the present work it has been the aim to pursue such methods and to keep such records of furnace events as will permit comparisons with future experimental work with the particular plant used. Details of these methods and records have been described at proper places in the report and care has been taken to point out irregularities that have occurred. Those methods toward which special study has been directed and which are perhaps of interest aside from their bearing upon the general results contained herein are:

(a) Method of sampling flue gases, see page 88.

(b) System for recording furnace observations and the details of furnace control in fuel tests with the chain grate stoker, see page 92.

II. THE COAL USED

4. *The Coal* used was selected wholly on account of the sizes represented and not for the purpose of comparing coals from various seams or mines in the State. Direct transportation facilities also influenced the selection because of limited storage capacity at the University.

Coal from washing plants in two districts was selected. That from Vermilion county is believed to be characteristic of the washed coal from the seam mined. Coal from this locality has been widely known as "Grape Creek" coal. The coal from Williamson county, including both washed and unwashed coal, is representative of the coal mined from Seam No. 7 in that and adjoining counties.

The stratigraphy of the seam mined in Vermilion county has been questioned for various technical reasons. The same seam characteristics as are found in Seam No. 7 mined in Williamson, Franklin and Jackson counties are, however, present, although the chemical properties of coals from the two seams show sharp differentiations.

5. *The Washing* plants now in operation in the State number about forty. With few exceptions round-hole revolving screens are used, but the size of coal prepared by these varies. By agreement, in 1903, the operators in Williamson county adopted the following standard of sizes for washed coal. The numbers used refer to screens with round perforations.

Designation	Through	Over
No. 1	3 in.	1 $\frac{3}{4}$ in.
No. 2	1 $\frac{3}{4}$ in.	1 in.
No. 3	1 in.	$\frac{3}{4}$ in.
No. 4	$\frac{3}{4}$ in.	$\frac{1}{2}$ in.
No. 5	$\frac{1}{2}$ in.	.....

This gradation has been, in the main, adopted, although several of the mines in that county are also supplying intermediate sizes to meet special market demands. Of the total number of washeries in the State, fifteen are supplying these sizes. Other grades of washed coal prepared by one or more plants are between screens of the following perforations:

Perforations inches						Screens
2	1	$\frac{1}{2}$	0	....	....	Round hole
$1\frac{1}{4}$	$\frac{3}{4}$	0	...	....	....	Round hole
3	$1\frac{1}{2}$	$\frac{7}{8}$	$\frac{3}{8}$	0	....	Round hole
3	$1\frac{3}{4}$	$\frac{3}{4}$	0	....	....	Square hole
3	$1\frac{3}{4}$	$1\frac{1}{4}$	$\frac{1}{4}$	0	....	Round hole
$2\frac{1}{2}$	$1\frac{1}{2}$	$\frac{1}{2}$	...	....	....	Round hole. Size below $\frac{1}{4}$ discarded.
$1\frac{1}{4}$	0	...	....	....	....	Washed screenings
3	$1\frac{3}{4}$	1	$\frac{1}{2}$	$\frac{1}{4}$	0	Round hole
3	$1\frac{3}{4}$	1	$\frac{3}{4}$	5-16	$\frac{1}{8}$	Round hole
3	$1\frac{3}{4}$	1	$\frac{3}{4}$	5-16	0	Round hole
$1\frac{1}{4}$	$\frac{3}{4}$	0	...	....	....	Bar screen

6. The tables given below show the character and grade of the coal selected for the experiments.

Table 1 gives the size and description of the coal. The screens in use at each of the mines are rotary screens with round perforations. The fuel symbol, column 2, in this and the tables following, is a convenient index number, adopted to facilitate the keeping of records at the testing plant. The integral number is the mine index while the remainder of the symbol refers to the size and condition of the coal. For example in the number 4.0703, 4 is the mine number. The remainder of the number gives the

TABLE 1 DESCRIPTION OF COAL

No.	Fuel Symbol	Commercial Name	Size of Screen	Condition	Kind of Washer	Location of Mine		Coal Seam
						Town	County	
1	2	3	4	5	6	7	8	9
1	4.0703W	Washed Pea.	$\frac{7}{8}$ - $\frac{3}{4}$	Washed	New Century	Westville	Vermilion	6
2	4.0703W	Washed Pea.	$\frac{7}{8}$ - $\frac{3}{4}$	..	..	..	..	6
3	4.0700W	W. Pea & Duff	$\frac{7}{8}$ -0	..	..	..	..	6
4	4.0300W	Washed Duff.	$\frac{7}{8}$ -0	..	..	..	..	6
5	5.1610W	No. 2 washed	$1\frac{3}{4}$ -1	..	Stewart	Herrin	Williamson	7
6	5.1006W	No. 3	1- $\frac{3}{4}$	..	..	..	..	7
7	5.0602W	No. 4	$\frac{3}{4}$ - $\frac{1}{2}$	..	..	..	..	7
8	5.0200W	No. 5	$\frac{1}{4}$ -0	..	..	..	..	7
9	6.0402W	No. 4	$\frac{1}{2}$ - $\frac{1}{4}$	..	Stewart	Marion	..	7
10	6.0200W	No. 5	$\frac{1}{4}$ -0	..	..	..	..	7
11	7.1610—	No. 2 Nut....	$1\frac{3}{4}$ -1	Unwashed	.....	Herrin	..	7

size of the screens used in preparing the coal. The number is given in the octonal system, e. g., 1.6 to 1.0, written for convenience .1610, indicates that the size is between $1\frac{6}{8}$ in. and 1 in.; .0703 indicates that the size is between $\frac{7}{8}$ in. and $\frac{3}{8}$ in.; .1006 that the size is between 1 in. and $\frac{6}{8}$ in., etc. Suffixed to these numbers W indicates washed coal and the dash —, unwashed coal. In Table 1, columns 4, 5, 7 and 8 define the meaning of the fuel symbols for every coal tested.

Table 2 gives the results of analyses of composite samples made up from the samples taken during the progress of the tests. The method of preparing these composite samples is explained on page 119. Sampling at the mine in view of the nature of the experiments was not considered necessary. None of the coal was stored for a greater period than six weeks after receipt so that except for changes in moisture content the analyses of the compos-

TABLE 2 AVERAGE COMPOSITION AND CALORIFIC VALUE
OF THE COAL AS FIRED

Analyses of Composite Samples													
No.	Coal Symbol	Chem. Lab. No.	Moisture on Air Drying	Coal as Fired									Calorific Value per pound
				Proximate Analyses									
				Fixed Carbon	Volatile Matter	Ultimate Analyses							
						Total Moisture	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	
1	2	3	4	32.2	33.2	34.2	35.2	37.2	38.2	39.2	40.2	41.2	
			%	%	%	%	%	%	%	%	%	%	B.t.u.
1	4.0703 W	608	14.46	41.45	32.10	18.97	7.48	58.72	3.90	8.36	0.98	1.59	10385
2	4.0703 W	253	13.10	41.35	32.36	18.03	8.26	59.28	3.82	7.85	1.00	1.76	10534
3	4.0700 W	302	12.55	39.30	32.90	18.78	9.02	57.22	3.75	8.55	0.98	1.70	10381
4	4.0300 W	600	17.43	36.49	28.73	22.00	12.78	52.05	3.42	6.60	1.11	2.04	9154
5	5.1610 W	502	6.04	50.44	31.72	9.60	8.24	66.62	4.53	8.57	1.17	1.27	11843
6	5.1006 W	571	4.74	51.18	30.76	9.27	8.79	66.49	4.19	8.86	1.24	1.16	11795
7	5.0602 W	273	7.77	48.50	30.18	12.14	9.18	64.62	4.11	7.54	1.16	1.25	11432
8	5.0200 W	303	11.62	43.26	28.89	15.69	12.16	58.81	3.66	7.42	1.08	1.18	10398
9	6.0402 W	304	7.16	49.50	32.44	10.69	7.37	66.97	4.28	8.13	1.20	1.36	11983
10	6.0200 W	587	13.89	44.20	26.62	18.17	11.01	57.00	3.56	7.58	1.23	1.45	10010
11	7.1610	519	2.83	50.82	32.24	7.45	9.49	66.78	4.30	8.59	1.25	2.14	12012

ite samples fairly represent the coal as delivered. Comparison of the amount of adhering moisture carried by washed coal can be justly made only by taking into account the lengths of haul in transportation, conditions of weather and the time since loading; so in this respect, only qualitative deductions should be drawn from the figures given for total moistures. Coal from the mine, Index No. 4, was usually delivered on the following day after washing and was loaded directly from the car into the boiler room. The coal from each of the other mines was several days in transit and was unloaded into roofed storage sheds. Test samples only were taken. The coal, 5.1006W remained in storage about six weeks before it was sampled.

Table 3 gives the results of analyses for the air-dry sample. These are original figures reported by the chemical laboratory. It is interesting to note that there is but small dif-

TABLE 3 AVERAGE COMPOSITION AND CALORIFIC VALUE
OF THE AIR-DRY COAL

Analyses of Composite Samples												
No.	Coal Symbol	Chem. Lab. No.	Air-Dry Samples									
			Proximate Analyses					Ultimate Analyses				
			Fixed Carbon	Volatile Matter	Moisture	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Calorific Value per pound
1	2	3	4	5	6	7	8	9	10	11	12	13
			%	%	%	%	%	%	%	%	%	B.t.u.
1	4.0703W	608	48.45	37.53	5.27	8.75	68.65	4.56	9.77	1.14	1.86	12141
2	4.0703W	253	47.58	37.24	5.67	9.51	68.22	4.40	9.03	1.15	2.02	12122
3	4.0700W	302	45.99	38.50	4.95	10.56	66.95	4.39	10.01	1.15	1.99	12149
4	4.0300W	600	44.19	34.80	5.53	15.48	63.05	4.14	7.99	1.34	2.47	11086
5	5.1610W	502	53.68	33.76	3.79	8.77	70.90	4.32	9.12	1.25	1.35	12604
6	5.1006W	571	53.72	32.29	4.76	9.23	69.79	4.40	9.30	1.30	1.22	12381
7	5.0602W	273	52.59	32.72	4.74	9.95	70.06	4.46	8.18	1.26	1.35	12395
8	5.0200W	303	48.94	32.69	4.61	13.76	66.55	4.14	8.39	1.22	1.33	11765
9	6.0402W	304	53.32	34.94	3.80	7.94	72.13	4.61	8.76	1.29	1.47	12907
10	6.0200W	587	51.83	30.91	4.97	12.79	66.20	4.13	8.80	1.43	1.68	11635
11	7.1610—	519	52.30	33.18	4.75	9.77	68.72	4.43	8.84	1.29	2.20	12362

ference in the amount of absorbed moisture in the different coals after air drying. The method of air drying is explained on page 101.

Table 4 gives a better comparison of the characteristic differences in composition of the fuel from the two localities represented. For analyses and heating values used in the calculation of the test results, see Tables 37 and 38, Appendix III.

TABLE 4 AVERAGE COMPOSITION AND CALORIFIC VALUE
OF THE ASH AND MOISTURE-FREE COAL

Analyses of Composite Samples										
No.	Coal Symbol	Chem. Lab. No.	Pure Coal (Ash and Moisture-Free Coal)							Calorific Value per pound
			Prox. Analyses		Ultimate Analyses					
			Fixed Carbon	Volatile Matter	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	
			%	%	%	%	%	%	%	B. t. u.
1	4.0703 W	608	56.35	43.65	79.85	5.30	11.36	1.33	2.16	14121
2	4.0703 W	253	56.10	43.90	80.42	5.19	10.65	1.36	2.38	14291
3	4.0700 W	302	54.43	45.57	79.24	5.20	11.85	1.36	2.35	14380
4	4.0300 W	600	55.94	44.46	79.81	5.24	10.12	1.70	3.13	14035
5	5.1610 W	502	61.39	38.61	81.09	5.51	10.43	1.43	1.54	14416
6	5.1006 W	571	62.46	37.54	81.14	5.12	10.81	1.51	1.42	14395
7	5.0602 W	273	61.65	38.35	82.12	5.23	9.59	1.48	1.58	14529
8	5.0200 W	303	59.95	40.05	81.53	5.07	10.28	1.50	1.62	14412
9	6.0402 W	304	60.41	39.59	81.72	5.22	9.93	1.46	1.67	14622
10	6.0200 W	587	62.41	37.59	80.50	5.02	10.70	1.74	2.04	14135
11	7.1610—	519	61.18	38.82	80.40	5.18	10.34	1.51	2.57	14462

III. SUMMARY OF RESULTS AND CONCLUSIONS

7. *The conclusions* herewith presented are based on 58 trials with washed coal and 6 trials of No. 2 unwashed coal.

The grades tested were regular commercial grades purchased at the mine, and with one exception, in which a mixture of two grades was tested, were of sizes representing common standards. Tests of eight standard grades covering a full range of sizes suitable for burning upon the chain grate are included.

Much of the work has necessarily been of preliminary character, but an endeavor has been made to obtain as general a

survey of the facts relating to the use of washed grades in connection with the chain grate stoker as was possible with the time and funds available. In making an analysis of the work, particular emphasis has been placed upon the modifying influence of methods of furnace control, the variations in the results due to radiation and conduction losses from the furnace and boiler, and the factors that influence the relative values of the fuels. Data not directly applied to the analyses made are presented in Appendix III.

It is shown in the analysis that results of tests direct with steam boilers may be only roughly compared, and that if close comparison of evaporative results is to be made, the amount of radiation and conduction losses must be known and corresponding corrections applied.

8. Concerning the principal points investigated, the following general conclusions may be drawn:

1. A comparison of fuels burned upon the chain grate is possible only when the fuel beds are kept in uniform condition. Irregularities that may occur in the fuel bed, whether induced by characteristics of the fuel or otherwise, may cause variations in the evaporative results for the same grade, which are wider than occur between any grades above the size $\frac{3}{8}$ in. to 0, when those grades are burned with the best care and attention.

2. Under the best care of the fuel bed (horse-power, depth of fuel bed, and other imposed conditions being equal), representative grades show the following relative economic values, based upon ash and moisture free coal:

Laboratory File No.	Size inches	Relative Total Heat Values	Relative Practical Heat Values	Relative Economy
5.1610 W	1 $\frac{1}{4}$ to 1	1.021	1.036	0.981
7.1610 —	1 $\frac{1}{4}$ to 1	1.020	1.038	0.994
5.1006 W	1 to $\frac{3}{4}$	1.022	1.036	1.039
4.0703 W	$\frac{3}{4}$ to $\frac{1}{2}$	1.000	1.000	1.000
4.0300 W	$\frac{1}{2}$ to 0	0.984	.983	0.778
6.0200 W	$\frac{1}{4}$ to 0	1.000	1.004	0.813

The ratios shown are taken with respect to the results for fuel 4.0703 W, and economy values are compensated for radiation and conduction losses from the furnace and boiler.

The ratios for the economy include the variations due to size, unequal practical heat value, and ash-pit loss.

The sizes used represent the range of sizes that are practicable for the chain grate stoker. The widest variation in economy shown is that between fuel 5.1006W and fuel 4.0300W, approximately 26 per cent with a variation of 3.8 per cent in the total heat values, and a variation of 5.3 per cent in the practical heat values.

It should be noted that the ratios for relative economy represent only one factor in the money value of the grades. Large sizes, it is known, have better shipping and storing qualities and are suitable for a wide variety of uses. Very fine sizes, on the other hand, require greatest attention in burning and increase the stand-by losses and fixed charges of the plant.

3. The effect of size, *per se*, upon resulting economy and thermal efficiency, i. e., apart from variation induced by differences in initial heat values and losses of heat, is characteristically shown by the quantities of air accompanying combustion. The weight of air per pound of combustible consumed and the percentage of excess air for the several fuels, taking for comparison the same conditions and tests as are used in the comparison (2) above, are as follows:

Index No.	Size inches	Pounds of Air per pound of Combustible Consumed	Excess Air percent
5.1610 W	1 $\frac{3}{4}$ to 1	21.05	81.76
7.1610 —	1 $\frac{3}{4}$ to 1	21.18	79.29
5.1006 W	1 to $\frac{3}{4}$	17.93	51.81
4.0703 W	$\frac{7}{8}$ to $\frac{3}{4}$	17.30	54.34
4.0300 W	$\frac{3}{8}$ to 0	28.05	135.87
6.0200 W	$\frac{3}{4}$ to 0	31.56	169.47

The fact that the order of the values for "Excess air, per cent" is slightly different from the order of the quantities in column 3, is due to a slight difference in the chemical compositions and theoretical air requirements of the combustibles consumed.

These values represent a combined characteristic of the size and grade under conditions of operation that maintained the fuel beds of the same area and gave to each fuel the attention that seemed necessary to produce best eco-

nomic results. The excess air for all grades may be further reduced by banking the fuel at the back of the grate, but as that condition jeopardizes economy through increased loss of fuel in the ash and refuse, it was not attempted.

4. Any rate of combustion or horse-power desirable for stationary practice may be obtained with any of the standard grades tested above the sizes $\frac{3}{8}$ in. to 0.

With the sizes $\frac{3}{8}$ in. to 0 and $\frac{1}{4}$ in. to 0, the boiler rating was obtained approximately, as a maximum result. With one shipment of the grade $\frac{1}{4}$ in. to 0, 175 H. P. was obtained as a maximum. For these small sizes increasing the draft would not further increase capacity. Careful attendance in burning fine sizes pays a big premium.

5. Comparisons of rates of combustion or horse-power for different fuels should be made on the basis of equal rates of air supply. Comparisons in that manner are shown on page 65.

6. For sizes above $\frac{3}{8}$ in. to 0, a slight tendency toward increased excess of air with increased rate of combustion is indicated, though no systematic relation is shown.

The thermal efficiency decreases slightly with increased rate and apparently in a linear relation. The horse-power is approximately proportional to the rate of combustion. Various grades differ in this respect, according to the proportion of excess air accompanying combustion.

The fine sizes produce their best results generally at their maximum rate of combustion. The size $\frac{3}{8}$ to 0 (fuel 4.0300W) is superior in this respect to the size $\frac{1}{4}$ to 0 (fuels 5.0200W and 6.0200W).

7. Increasing the thickness of the fuel bed results in a decrease in the loss of fuel in the ash and refuse. In some cases there results also a slight decrease in excess air, but in other cases a slight increase results. No definite relation depending upon the size of the grade is shown in the latter respect.

The maximum difference shown in over-all efficiencies due to carrying different thicknesses of fuel bed is approximately 2 per cent for gate openings varying from 4 to 7 in.

IV. GENERAL CONSIDERATIONS AND DEFINITIONS

9. In the analysis of the performance of steam generators it is sometimes thought to be useful to define in some detail, the functions of the separate parts of the generator, such as the grate, the combustion space, the boiler, etc. The boiler is easily differentiated from the other parts of the steam generator, but to ascribe a definite division of duties to the furnace parts involves arbitrary assumptions and definitions. Consequently, terms vary in meaning in the literature of the subject and depend upon the view point of the writer. For the purposes of the present work, it will be necessary to make only one division, i. e., the boiler and the furnace and to define them as follows:

10. The *Boiler* is a definite arrangement of heating surfaces including any fixed arrangement of gas baffles that may be used for the purpose of directing the course of the heated gases over the heating surfaces.

The *Furnace* includes the combustion space, the grate or mechanical stoker, incidental brick work and enclosing walls.

Certain parts of the furnace, arches in particular, are essential for the ignition and proper combustion of the fuel in mechanical stokers and, in general, the form of the brick parts is determined by the stoker or the grate. The tile roof of the Heine combustion chamber is a feature of the boiler and also a feature of the furnace.

11. A division according to function is not so simple. The sole function of the boiler is to absorb heat, and with clean heating surfaces its characteristics are definite. In order that the heat in the coal may be actually available for transmission to the boiler, it must be developed and transferred in gases, or by radiation from the fuel bed and flames, at temperatures above that of the heating surfaces. Since a considerable part of the heat is always contained in the gases below the temperature of the heating surface, the economy of the process increases as the heat contained in the gases above the temperature of the heating surface increases. The available heat in the gases at any given temperature is, of course, only the heat that is used to increase the temperature of the gases, i. e., the so-called sensible

heat. However as the gases are cooled in their passage over the boiler surfaces, the part of the heat that was used in doing the work of expanding the gases in the furnace is directly used by the boiler. For lack of a more definite term, the term heat content used in the following discussion is taken to include both the sensible heat and the heat required for the work of expansion. The heat content is proportional to the temperature of the gases and the mean specific heat at constant pressure. Denoting by Q the heat content of one pound of the gases we have, therefore,

$$Q = C_p T.$$

The gases are the principal means of conveying heat to the boiler, when the furnace is of the kind used in this work, but where much heat reaches the surfaces by direct radiation, as in plain tubular, locomotive, and internally fired boilers, the problem is much complicated. It is intended, however, to deal here with a single type of plant in which there is reason to believe that but a small proportion of the total heat reaches the heating surface by direct radiation, i. e., by transmission through the tile roof. However, whether the process of heat transfer from the fuel to the boiler is by conduction from gases alone or is a mixed process, it is nevertheless true that economy in the utilization of the heat from the coal increases as the sensible heat content of one pound of gas increases.

12. *Furnace Effect.*—For brevity, and significance as well, the “heat content of one pound of the gases” delivered to the boiler will be termed the *furnace effect*. The factors that operate to modify the furnace effect are:

1. Total heat value of the coal.
2. Latent heat in the moisture formed by the burning of the hydrogen in the coal.
3. Latent heat in the moisture evaporated from the coal.
4. Undeveloped heat in smoke and incompletely burned furnace gases.
5. Proportion of air supplied to fuel consumed.
6. Radiation and conduction from the furnace parts.
7. Loss of heat in hot ash and refuse.

The first, second, and third factors determine the quantity of heat from the coal that will be available for producing rise of temperature. The total heat value of a coal as determined by means of the combustion bomb calorimeter is the heat that would be available by cooling the combustion gases to the temperature at which the combustion was initiated, i. e., room temperature—usually about 70° F. Thus the heat that becomes latent in furnace processes is included in the reported total heat value of the coal.

The total heat minus the latent heat of the moisture is usually termed the *practical heat value* of the coal. It may be calculated as follows:

Let H = the total heat value, B. t. u. per lb.

m_1 = the moisture in the coal by weight per lb. of coal.

m_2 = the moisture formed in the burning of the hydrogen by weight per lb. of coal.

Then Practical heat value = $H - 966 (m_1 - m_2)$

Ash and moisture in coal are extremely variable and may be considered extraneous and as adding nothing of value. They are properly considered as diluents in considering heat values and may thus readily be taken account of in the purchase of coal. Because of the variability of ash and moisture content and the ready manner in which they may be accounted for by simple analysis, comparison of the practical effects of different types of coals is most satisfactorily based upon the unit of "combustible", i. e., ash and moisture free coal. This unit is termed by some writers "pure coal"; the usual designation combustible as used in the A. S. M. E. code is adhered to herein.

To give a rough idea of the variation in the furnace effect due to differences in practical heat values per unit of combustible, consider two Illinois coals having heat values of 13950 and 13500 B. t. u. respectively, and assume an air supply of 14 pounds per pound of combustible. Thus approximately 15 pounds of gas is formed and neglecting radiation and conduction losses, etc., the furnace effects are 930 and 901 B. t. u., respectively.

The quantity of air used, however, may vary between 14 lb. and 40 lb., giving with the latter quantity furnace effects of 340 and 330 respectively, for the two combustibles. In bad furnace operation as much as 50 pounds or more of air used per unit of combustible is not infrequently found. This illustration has been given to show the relative influences of the fifth factor given above and of the heat values of coals.

The effect of a higher heat value in coal must, of course, be a beneficial one, but the evaporative effect obtained in actual operation at times due to conditions that cause disproportion of the air supply may indicate even the reverse. The decrease in the furnace effect due to radiation and conduction from the furnace varies with the area of the exposed wall surface of the setting, the temperature within the furnace, specific conductivity of the walls, temperature of the surroundings, and drafts of air through the boiler room. Its real value in any instance has never been directly determined.

The fourth and fifth factors, it is well understood, can be modified either in the direction of good effect or of bad effect by the features of the furnace, the fuel, and the manner of operating the furnace. The importance of the proper proportion of the air supply has been indicated. The proportion of air to fuel consumed is affected by care or indifference in operating, mechanical conditions of the fuel, and leakage around the edges of the grate. These same conditions play an important part in determining the amount of smoke and incompletely burned furnace gases. The construction of the grate or mechanical stoker and the combustion space are important elements in determining the latter factor. Conditions affecting air proportion, smoke and incomplete combustion vary from those of poorly constructed and poorly operated hand-stoked furnaces and mechanically-stoked furnaces to excellent construction and operation in both, but whether a hand-stoked furnace or a mechanically-stoked one, the personal factor of the operation does not lose its importance.

The seventh factor may be disposed of as negligible for practical purposes.

This involved condition of affairs makes it impossible to assign the function of producing good furnace effect to any one element alone, or, on the other hand, to assign to any single element a function not involved in the function of other elements.

13. *Service Value of a Fuel.*—In view of the involved nature of the influences just noted, it will easily be understood why the application of the results obtained in evaporative tests of fuels is restricted in application to the particular types and combination of boiler and furnace in connection with which the tests were made, and further are especially restricted by the particular conditions of the furnace control.

For the purpose of comparing the economy of fuels, the heat absorbed by the boiler per pound of fuel should be based upon the fuel fed to the furnace. The results then take into account the loss of fuel from the grate. Conditions of the furnace operation in comparative tests are usually either very carefully controlled or they are the usual operating conditions in the plant where the tests are made. In either case loss of fuel in the ash and refuse is chargeable to the character of the fuel, the characteristics of the grate in that respect, and the conditions of operation. In a summary of experimental results, page 50, the term "service heat value" is used to designate the value of the fuel as found under test with a particular combination of boiler and furnace, operated under specifically controlled conditions.

By the term "service heat value" is meant the quantity of heat (B. t. u.) absorbed by the boiler and delivered to the steam per pound of fuel fed to the furnace. The expression of the economic result in B. t. u. is more convenient for comparison with the total heat value of the fuel than if expressed in pounds of water evaporated per pound of fuel. Otherwise, either manner of expressing the economic result is equally useful.

The heat absorbed by the boiler depends mainly upon the furnace effect and whatever modifications of results are due to the characteristics of the boiler. When, however, the resulting absorption is expressed on the basis of one pound of fuel, the heat delivered to the boiler per pound of fuel is a measurable factor. It is the difference between the total heat value of the fuel and the sum of the losses due to incomplete combustion, latent heat in moisture, loss of fuel from the grate and radiation and conduction losses from the furnace. The furnace effect is equal to this difference divided by the number of pounds of moist combustion gases resulting per pound of fuel. Evidently it is possible in two different operations to have equal furnace effects with unequal quantities of heat delivered per pound of fuel. This condition may result from a difference in the initial heat value of the fuel or a difference in the sum of the losses. Necessarily different weights of gas per pound of fuel will be required in two cases: and since the rate of heat transmission depends upon the temperature of the gases above the temperature

of the heating surface a different heat absorption per pound of fuel must result.

14. *Efficiencies*—Two expressions for efficiency are used in this report. They are termed respectively.*

Over-all efficiency, E_1 .

Efficiency of the boiler and furnace, E_2 .

The reason for adopting these terms in place of the usual ones which are given in the code of the A. S. M. E. for boiler testing, should be evident from the preceding remarks. The A. S. M. E. code expressions are:—

“Item 72. *Efficiency of boiler*: heat absorbed by the boiler per pound of combustible consumed divided by the heat value of one pound of combustible = Item (71 x 965.8) — Item 51.”

“Item 73. *Efficiency of boiler, including the grate*: heat absorbed by the boiler per pound of dry coal fired, divided by the heat value of one pound of dry coal

= Item (70 x 965.8) — Item 50.”

Item 72, as it is now defined in the A. S. M. E. code, is not the efficiency of the boiler alone, but includes also the furnace, the influence of the fuel characteristics, and the variation and faults of operation; in fact, all of the factors that cause variation in the value found for Item 73 with the exception of the ash-pit loss. That is, Item 72 and Item 73 are identical in their main import; they are both measures of composite effects, the only difference being that in Item 73 a charge is made against the plant for the heat of the total weight of fuel fired while in Item 72 the charge against the plant excludes one variable.

E_1 is calculated herein in the same manner as in the A. S. M. E. code Item 73, and E_2 is calculated in the same manner as the A. S. M. E. code Item 72, and in the report these item numbers are used to designate them. The only difference is in the less ambiguity of the terminology. As a matter of fact, the term “boiler and furnace” efficiency is ambiguous unless it is kept in mind that it is merely the over-all efficiency compensated for the ash-pit loss.

In the discussion of results and in Tables 5 to 14 these efficiencies have been compensated for the heat lost in the water-back,† the corrected items being designated by “Item 72.1” and “Item 73.1.”

*These terms were suggested by L. P. Breckenridge, Jour. W. Soc. of Engrs. XXII. 3, 288.

†See pages 115 and 116.

15. *Rate of Combustion.*—From the standpoint of theoretical chemistry, each constituent in the heterogeneous mixture of carbon and hydrocarbons which make up coal substance should, under isothermal conditions, have a definite velocity with which it will react with oxygen. And, in general, the different components have different rates of reaction, the more so because many of the hydrocarbons wholly oxidize only after volatilization and subsequent successive changes in chemical structure.

Oxidation of these compounds takes place slowly at ordinary temperatures, but at temperatures approaching those of industrial furnaces, the velocity of oxidation is so enormously accelerated that we never note any practical difference in the rate of combustion chargeable purely to differences in the velocity of oxidation of different fuels.

Experience shows that as rapidly as we can supply air to the fuel it will be burned. Differences in rate of combustion in a practical sense are wholly due to conditions that prevent the air from coming in contact with the fuel, and to the amount of air supplied.

With fine sizes of coal the rate of combustion is limited by the rate of air supply that disrupts the fuel bed and permits air to pass through without coming into contact with the fuels. This limit is reached with very fine-sized coals and with screenings containing much dust, and is a serious circumstance in steam generation because of a natural tendency of the fireman to increase the draft when there is demand for more steam. This maximum limit in the rate of combustion is one of the important factors which determine the selection of fuel for a particular condition of service. To discover just what this maximum limit is and to determine its relation to the draft pressure is an essential item to be observed in experimental testing.

For those grades of fuel that do not exhibit a maximum rate of combustion within the limits of practical demands, and below that limit for those that do, it is important to know the relation between characteristics of the grade, the draft conditions, and air supply. For a useful and practical consideration of these features, it is imperative that the following points should be recognized.

In a practical sense the weight of fuel that can be burned in a given time is determined by two principal factors.

(a) The rate at which air is supplied to the fuel.

(b) The efficiency with which the air is utilized.

The relation of these two factors is apparent at once, for if we consider two equal fuel bed areas to be supplied with the same volume of air per unit time, that one will be most rapidly consumed which utilizes the air most completely. On the other hand if the air in both cases is utilized to the same extent, the relative rates of combustion will be directly proportional to the rate of air supply.

The first factor (a) is the one most usually considered as determining the rate of combustion. The second factor (b) is rarely given proper consideration. Its significance will be seen when it is recalled that for a given rate of air supply, the rate of combustion will be approximately twice as great with 12 per cent of carbon dioxide in the flue gases as with but 6 per cent.

The second factor (b) is that to which we have charged the variations in the furnace effect, and the same causes, viz., character of the fuel, leakage, degree of care in attendance, which affect the furnace effect by dilution of the combustion gases, act under fixed draft capacity to modify the rate of combustion.

The first factor depends upon the resistance of the fuel bed and grate, and the available draft pressure and draft capacity. The resistance of the fuel bed varies with the size of the fuel, the thickness of the fuel bed and the amount and character of caking and clinkering.

V. TEST RESULTS

16. As stated elsewhere in the discussion of results, the present report is concerned with that part of the data most directly related to the fuel. In Appendix III many data are presented which, it is hoped, aside from the intrinsic value, may be found useful to those who may wish to review the work critically.

Limitations of results. In comparing the characteristics of the different grades of coal, it has been a problem of serious concern as to how much attention should be given to the fuel beds.

Some fuels require little attention, while others have a characteristic tendency to burn out in spots or clinker more or less seriously. The furnace attendant naturally judges the quality of the coal by the amount of attention required to keep up steam. Thus, since this feeling is a general one, it would be of interest to compare fuels under equal attention all around for certain special plant conditions. To adopt such methods for test purposes, however, would be to place upon large grades of coal a premium which they do not deserve, when market prices are considered. Moreover, a hesitating demand for certain of those grades which require much attention has been a factor in maintaining them as cheap fuels, although more than sufficient pecuniary advantage to offset the extra care required may be obtained from their use.

17. Mechanical stokers, which feed by continuous progression of the fuel over the surface of the grate, or in which the grate itself progresses through the furnace, and which are therefore continuously self-cleaning, are adapted to a wide range of fuels. A feature of these self-cleaning types is the difficulty of proportioning the air supplied to the furnace, especially when the fuel is not uniform or is of very fine size. The nature and depth of the fuel bed changes gradually from the feed gate to the end of the grate, and an excess of air is admitted where least needed by the fuel. The stirring action of inclined stokers, though an advantage with mildly coking coals, is unnecessary with moderately free-burning coal and tends to distribute the air unevenly. Combustion upon the chain grate is free from this particular source of dilution since the fuel bed may remain undisturbed during combustion. Excess air through the thin fuel bed at the rear of the grate, and leakage into the furnace between the bridge wall and the end of the grate, or through the dump grate of the inclined stoker can not be readily controlled. Devices applied to the chain grate for preventing undue leakage, such as over-hanging bridge walls with or without water-backs, designed to permit just sufficient room for the passage of the ash, and the various forms of dampers under the grate and in the ash-pit, are only moderately successful.

A feature of such mechanical stokers, which largely operates to offset the disadvantages just noted and which make them particularly adapted for efficient combustion of high volatile coals, is the ignition arch under which the fuel passes as it enters the

furnace. On account of the depth of the fuel bed under the arch, the air supply there is retarded and is insufficient for the complete combustion of the volatile matter distilled off in large amount at that place. If the combustion space is properly constructed, this volatile matter can mix with the diluted gases from the thinner portion of the fuel bed and be burned. Thus a proper proportion of excess air through the rear portion of the fuel bed is an advantage.

In the case of the traveling grate, the importance of carefully standardizing the furnace control in practical testing is emphasized by the following fact. By driving the grate faster than the fuel is consumed and thus passing burning fuel over the rear end into the ash-pit, the excess air at the rear end may be largely utilized, and the result is, of course, a higher furnace effect and consequently higher "boiler and furnace" efficiency, but because of loss of fuel the over-all economy is decreased. This possibility is sometimes taken advantage of in tests in which it is desired to show a high "boiler and furnace" efficiency with a given coal, and in practical operation under conditions where the demand for high boiler horse-power temporarily sets aside considerations of economy.

18. *Control of the Furnace.*—In outlining the tests of these experiments an effort was made to so standardize the operating of the furnace that the details of the control during each test might be made a matter of record. General features of the furnace control, which should be noted because of their bearing upon the test results, are set forth in the following paragraphs.

19. *Depth of the Fuel Bed.*—This was taken as the depth of the gate opening since an accurate estimate of the average depth of the grate could not be made.

20. *Area of the Fuel Bed.*—The area of the fuel bed was maintained as nearly as possible the same for all fuels, regardless of the frequency of adjustment required by the stoker-driving engine. Throughout all the tests, it was specifically understood that the fuel should not be allowed to bank against the water-back nor the live fuel line recede from the water-back a greater distance than was absolutely necessary. An attempt was made to hold the live fuel about 4 inches short of the water-back; the regulation of the small stoker engine, however, could not be depended upon so that this condition could not be exactly met. The difficulty was augmented in the early tests by trouble with the draft engine and by the conditions under which those tests were made.

21. *Attention Given to the Fuel Bed during Operation.*—During the tests No. 1 to 20 attention to the fuel bed was confined to occasional leveling. The object was to observe the performance with minimum attention to the fuel beds. At no time, however, were irregularities in the fuel bed allowed to become serious. During tests No. 20 to 64, it was sought to bring out the best possibilities with each fuel. In these tests, thin spots and humps at the rear edge of the bed were leveled and fuel was frequently pushed against the ledge plates to regulate leakage of air.

22. *Regulation of Draft Pressure.*—The following convention was adopted to define the draft pressure of the furnace. The *normal draft pressure* is that pressure upon the fuel bed which exists when the fuel bed is of the regular area assigned for all tests, when the fuel bed is without thin spots, and when the leakage along the ledge plates is not greater than normal. A normal draft pressure was assigned for each test on the day previous to the date of the test. This made it possible for the firemen to regulate the conditions some time before the start.

23. *Rate of Combustion.*—As closely as possible an even rate of combustion was maintained throughout each test.

24. *Fine Coal From the Drip Plate.*—The fine coal which fell through the grate was returned to the feed hopper and again fed to the furnace. This was done more frequently than usual under ordinary plant operation, the attempt being to distribute the fine coal uniformly.

25. *Leakage at the Rear of the Grate.*—The automatic water-back in all tests except one was allowed to ride upon the ash and clinker, so that the leakage of air passing to the furnace over the rear of the grate was as nearly as possible independent of the character of the fuel and other conditions save the draft pressure.

26. The record of the furnace conditions was carefully kept during each test. An explanation of the furnace record is given on page 92, and Table 40, Appendix III, comprises a summary of as much of the data contained in those records as is possible to represent in tabular form. Essential parts of the record which could not be so summarized have been kept in mind in modifying conclusions concerning the fuels.

VI. ANALYSIS OF RESULTS

27. For purpose of more ready comparison, important items from Tables 28 to 40, Appendix III, together with items not elsewhere presented, are set forth in this chapter, and certain of the relations shown graphically by means of charts. General explanations of the tables and charts follow.

28. *Tables.*—At the head of each table is given the fuel index number. The commercial sizes in fractions of inches are given in Table 1, page 4.

Column 1, series test number.

Column 2, depth of fuel bed in inches.

Column 3, draft pressure on the fuel bed in inches of water. This is the drop in pressure through the fuel bed. See page 116.

Column 4, pounds of combustible consumed per square foot of grate surface per hour = code item 30 $\div$ 38.2. This item represents the actual combustion. For the purpose here intended it is a better expression for the rate of combustion than "pound of dry coal per square foot of grate surface" since it removes non-essential variations due to differences in the percentage of ash and in the loss of fuel to the ash-pit.

Column 5, Horse-power developed, Item 65.1. In this column the actual horse-power developed is compensated for the heat lost to the water-back as explained on page 106. Its use removes a minor variation of from 1 to 3 per cent due to that loss. The items are derived from Item 65, Table 34.

Column 6, Horse-power developed per square foot of grate surface = Item 65.1 $\div$ 38.2.

Column 7, Per cent of builders' rating developed = Column 5 $\div$ 210.

Column 8, Efficiency of "boiler and furnace". See Item 72.1 page 115 and Table 35.

Column 9, Over-all efficiency. See Item 73.1 page 116 and Table 35.

Column 10, Per cent of total combustible lost in the "ash and refuse" = (Item 31 $\times$ Item 44) $\div$ (100 — Item 42). See Tables 29 and 38 for Items 31, 42, and 44.

Column 11, per cent of CO_2 in dry flue gases. See Table 36 and page 117.

29. The graphical representation of data presented in these tables is shown in Fig. 1 to 9.

These curves are not to be taken as representing mathematically definable relationships, and for this reason it may not be without value to call attention to the following considerations. For the most part the curves represent functions of two or several variables. For example, plotted points for the amount of air used per pound of combustible consumed and the resulting gas composition, should be expected to show only whether the excess of air varies with the rate of combustion and draft pressure. Since the drop in draft pressure is largely affected by the velocity or volume of gas flowing and its temperature, plotting points for this drop against rate of combustion is not wholly illogical, and reference to the points on the carbon dioxide curve or air supply curve will generally indicate the principal cause of variation. The carbon dioxide resulting from the combustion of a uniform coal composition is a function practically of the weight of air used per pound of combustible consumed, and with a constant per cent of CO_2 the volume of air flowing gives a directly proportional rate of combustion.

The general relation of these various factors, one to the other, is not difficult to understand, though the practical mathematics of the relations is somewhat tedious and will not in general permit of exact or in some cases even approximate interpolation between plotted points affected by a third variable; yet with proper consideration, the curves illustrate sufficiently well the relations under the conditions of the experiments. The resulting carbon dioxide percentages have been plotted in each of the charts as a datum of reference. The relation between the per cent of carbon dioxide and the furnace effect and temperature of combustion is very nearly a direct proportion, so that it will be apparent at once that the possibility of representing the data for certain fuels in the form of smooth curves has depended largely upon slight variation in the carbon dioxide conditions. In the charts showing air supply and draft pressures, uniformity of the fuel and furnace operation adds to the uniformity of the curves. The values for air

supply data are given in Table 24, page 72. Graphical representation is made only for those fuels that were tested at various rates of combustion.

30. *Fuel 5.0602 W*, Table 5.—Fuel of this grade, commercially known as No. 4 washed coal, is very uniform, and when it is burned upon the chain grate, the fuel bed usually requires little attention beyond care in the regulation of the grate and the occasional removal of clinker accumulating along the ledges. The tests of this fuel included in Table 5 were conducted under conditions of ordinary careful furnace control. Table 34 should be referred to.

TABLE 5 FUEL 5.0602W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
6	4	0.102	19.74	218.4	5.71	104.0	66.66	64.72	2.91	* 7.04
7	4	0.104	20.89	232.5	6.09	110.7	67.12	63.60	5.32	*10.10
8	5	0.090	19.71	216.3	5.66	103.0	66.16	64.42	2.63	* 9.54
9	6	0.134	20.65	215.8	5.64	102.8	62.93	61.87	1.74	* 9.47
10	7	0.162	20.13	210.5	5.51	100.2	63.09	62.00	1.73	* 8.22
11	6	0.150	20.16	216.3	5.66	103.1	64.38	62.91	2.20	* 8.05

*See page 117.

Four thicknesses of fuel bed were tried. The resulting efficiencies are in favor of the 4- and 5-in. beds. The smaller values for the 6- and 7-in. beds are due in part to irregularity of grate performance. On the whole, the furnace control for tests 9, 10 and 11 was less favorable to the fuel than that for tests 6, 7 and 8.

In all these tests, as will be noted generally, the greater ash-pit losses occur with the thinner fuel beds. The flame from this fuel was practically burned out at the rear of the combustion chamber, and no smoke was observed save in tests 10 and 11 at times when the fuel was banked against the water-back. See definition of "banked", page 94. The smoke for those periods was less than the shade represented by Ringelmann chart No. 2,

the average for each test being 0.08. See Column 12, Table 36. No trouble of any sort was experienced from clinker.

From the test results, it must be concluded that this fuel may be burned with no attention to the fuel bed, with resulting "boiler and furnace" efficiencies from 64 to 67 per cent, and over-all efficiencies from 62 to 65 per cent. With better attention to the fuel bed and more uniform regulation of the grate travel, this fuel would give as good results as those of Tables 8 and 14.

31. *Fuel 5.0200 W*, Table 6.—Washed coal of this grade passing a $\frac{1}{4}$ -in. round hole screen is generally known as No. 5 washed coal. Though made up of a narrow range in sizes, the proportion of intermediate sizes and especially the amount of dust contained may vary considerably in the washing process, and for this reason considerable variation in results must be expected even with coal from the same washery. The coal forms a very compact fuel bed, so that these slight changes in the proportion of intermediate sizes may produce a very considerable variation in the draft requirements. Six tests were made on this coal to determine the conditions favorable to maximum rate of combustion and evaporation. As in the preceding tests, the furnace control was that of good plant practice.

TABLE 6 FUEL 5.0200 W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
12	5	0.270	20.18	179.5	4.70	85.5	54.08	49.76	7.98	*7.10
13	6	0.380	21.54	193.6	5.07	92.2	54.47	51.14	6.12	*6.40
14	6	0.430	21.65	195.5	5.12	93.0	54.84	51.96	5.11	*5.84
15	4	0.290	24.01	216.8	5.67	103.2	54.88	49.17	10.32	*7.02
16	4	0.270	22.62	207.3	5.43	98.7	55.76	49.95	10.27	*5.95

*See page 117.

On account of the fineness of the coal and because of the closeness of the fuel bed, fuel of this size burns best when the force of the air passing through the fuel is sufficiently great to keep the finer particles continually agitated. To carry the draft much beyond this results in trouble. Holes develop rapidly, the increasing rush of air through such spaces reduces the draft pressure, and the rate of combustion is retarded over the entire bed. Reducing the draft much below the best condition not only retards the combustion, but gives the leakage of free air along the ledge plates and at the back of the grate an increasing weight in the total.

The proper draft pressure for the 6-in. bed was between those used. Practically the same rate of combustion was obtained with draft pressures of 0.38 and 0.43 respectively. In test 13 the fuel bed was dead and without serious tendency to form holes, as shown by the data in columns 9, 10 and 11, Table 40, while in test 14 considerable trouble resulted from the formation of holes over the back half of the grate, and the draft pressure varied widely at times. Tests 15 and 16 with a 4-in. gate opening gave most uniform results throughout, but required a high speed of grate travel. See Table 40. The chief trouble with a 4-in. bed was the tendency to burn out at the back end, requiring very careful regulation of the grate travel. For practical purposes a 4-in. fuel bed is too thin for this grade. With the 5-in. gate opening, test 12 gave very satisfactory results in every way except that the draft pressure was too low for maximum results. This was shown by the dull flat appearance of the fuel bed.

From these tests, the general conclusion can be drawn that under good plant practice there may be developed with this fuel for each square foot of grate surface, from 4.5 to 5.5 horse-power at "boiler and furnace" efficiencies from 54 to 56 per cent, and overall efficiencies from 49 to 52 per cent.

32. *Fuel 4.0700 W*, Table 7.—This fuel is a combination of the two grades, 4.0703W, Table 14, and 4.0300W, Table 13, the mixture containing about 30 per cent of the latter. At the washery, the component grades are washed separately and upon special order combined in varying proportions by running the products into the same bin. Subsequent handling in loading and unloading is depended upon to give a uniform mixture. On account of a fairly even gradation of sizes and the wet condition of the coal, this is ordinarily sufficient.

It was not intended at the time these tests were made, to extend the work to include mixtures of the standard commercial grades, but this car having been received by a mistake in billing, the four tests were made in view of the indications they might give as to the advisability of taking up such a series, and in that connection the results are interesting.

The tests were made under essentially the same conditions as those of Table 5, but the control of the fuel bed area, affected by more uniform regulation of the grate travel, was superior.

TABLE 7 FUEL 4.0700W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
17	5	0.130	19.92	213.3	5.58	101.6	65.31	62.23	4.71	*10.50
18	5	0.130	20.18	225.1	5.89	107.2	67.79	65.42	3.56	*10.60
19	4	0.106	20.39	224.9	5.89	107.0	67.04	64.69	6.66	*11.20
20	6	0.145	20.73	228.6	5.98	108.8	66.80	64.68	3.33	*9.94

*See page 117.

This fuel burned with as great uniformity as fuel 4.0703W or 5.0602W, but required slightly higher draft pressure. The fuel bed remained in good condition, though burning more rapidly along the ledge plates. It will be noted that the ash in this coal was greater and more irregular, due, no doubt, to the admixture of the finer size, but it appears to have had no effect on the economy or to have caused trouble from clinker. Combustion was complete and without smoke, and in every respect the tests of this fuel indicate that it is as suitable for use with the chain grate as either the fuel 4.0703W or the fuel 5.0602W. How much the rate of combustion may be increased over that shown by the tests can not be exactly stated. Nevertheless, close observation of furnace conditions leads to the conclusion that at least 25 pounds per

square foot is possible, a value which represents approximately seven boiler horse-power per square foot of grate surface. There is also no apparent reason why the economy obtainable with this mixture may not be increased by increased attention to the fuel bed.

33. *Fuel 6.0402W*, Table 8.—The tests here included are the first of the series in which the fuel bed was given the attention

TABLE 8 FUEL 6.0402W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 66.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
21	6	0.127	19.74	233.0	6.10	111.0	70.92	67.84	4.35	*12.40
22	7	0.138	19.03	218.4	5.72	104.0	68.46	66.98	3.01	*11.01
23	5	0.105	17.28	207.6	5.43	98.9	72.24	68.90	4.63	*11.79
24	4	0.085	19.55	232.3	6.08	110.6	71.65	68.56	4.31	*12.08
27	6	0.122	20.24	226.2	5.92	107.7	67.25	65.84	2.11	* 9.60

*See page 117.

that seemed necessary to keep it in uniform condition. Reference to Table 40 will show that undoubtedly more leveling was done than necessary. This fuel is similar in all respects, as to composition and grade, to the fuel 5.0602W of Table 5; both are from the same seam in Williamson county.

As with the fuel of Table 5, all of these tests were run at about the rated capacity of the boiler. There can be no question, however, that any capacity desirable can be obtained with this grade.

In test 27 of this group, the water-back worked stiffly and had to be supported free from the fuel bed. The test should be excluded for that reason. The remaining tests show but small differences in efficiencies with reference to the thickness of the fuel bed, what advantage there is being with the thinner fuel beds, though the tendency toward increased ash-pit loss with the thinner beds is again indicated. No trouble was experienced with clinker, and though the flame extended through the combustion chamber, the fuel was burned without smoke.

34. *Fuel 5.1610 W*, Table 9.—This fuel is a larger grade of washed coal than is usually burned upon the chain grate. That it

TABLE 9.—FUEL 5.1610W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per. hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
25	6	0.122	17.88	204.7	5.36	97.4	68.16	64.47	5.43	*10.30
26	6	0.122	20.10	227.1	5.95	108.2	67.97	65.35	3.85	*10.00
28	7	0.145	19.35	213.7	5.59	101.8	66.38	65.19	1.82	** 8.88
29	6	0.124	19.06	209.6	5.48	99.8	66.28	64.52	2.69	** 8.88
30	5	0.103	19.61	215.3	5.64	102.5	66.14	64.18	2.96	9.38

is not commonly burned is due, however, to a relatively higher market price and not to any difficulties arising from its use. Except for minor variations in the area of the fuel bed for tests 25 and 26, the conditions under which these tests were run were exceptionally uniform.

Attention should be directed here to the change in the methods of taking gas samples in the interval between tests 27 and 28. A source of leakage in the gas samples was detected and remedied during test 29.

The results of tests 28, 29 and 30 are accepted as representing the comparative economy obtainable with this grade of fuel under the conditions of these tests.

But five tests could be made with this fuel and these were given over to the determination of the effect of thickness of the fuel bed. It is well known that rates of combustion may be obtained with this fuel far beyond any present practical requirements. Referring to the three directly comparable tests 28, 29 and 30, a tendency toward increased ash-pit loss and decreased over-all efficiency with decreasing thickness of fuel bed will be noted. No variation in the boiler and furnace efficiency is shown. See effect of radiation and conduction losses, page 52.

*See page 117.

**Leak in gas sampler.

This fuel ignites readily under the arch. A long flame results but with combustion completed within the combustion chamber. The percentage of clinker was very small and after experience in the first two tests, the regulation of the grate and fuel bed was easily maintained

35. *Fuel 7.1610 Unwashed*, Table 10.—This coal and the washed coal of Table 9 were obtained from mines located about two miles apart at Herrin, Illinois. Both belong to No. 7 seam and are of the

TABLE 10 FUEL 7.1610—

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
31	5	0.093	19.32	216.2	5.66	103.0	65.90	64.40	2.45	9.32
32	6	0.124	18.90	212.0	5.55	101.0	67.82	66.35	2.30	*9.00
33	7	0.143	20.44	223.7	5.86	106.6	65.97	64.56	2.15	9.40
34	6	0.116	21.02	231.9	6.07	110.4	66.13	64.58	2.31	9.47
35	6	0.157	23.40	253.0	6.62	120.4	64.48	63.12	2.14	9.52
36	6	0.188	26.05	275.0	7.20	131.0	63.81	62.35	2.25	9.02

same ultimate chemical composition and heating value and in every respect similar, with the exception of a slightly greater ash and sulphur content in the unwashed coal.

The small difference in ash content did not warrant any expectation of different results in the combustion tests, yet to satisfy any doubt, tests 31, 32 and 33 were made under conditions similar to those of tests 28, 29 and 30.

The occurrence of clinker, though not serious with either fuel, called for some extra attention in burning the unwashed fuel, as shown in column 7, Table 40; otherwise the results are similar.

The remaining tests of this coal were run at increased rates of combustion. Comparison of the six tests in that respect show no positive change in the results charged to the fuel and stoker.

*Slight dilution of sample due to leak.

Both ash-pit loss and the excess air in the combustion gases remain practically constant.

Since the coal of Table 9 and that of Table 10 practically represent the same grade, the results obtained are plotted together in Fig. 1 and 2.

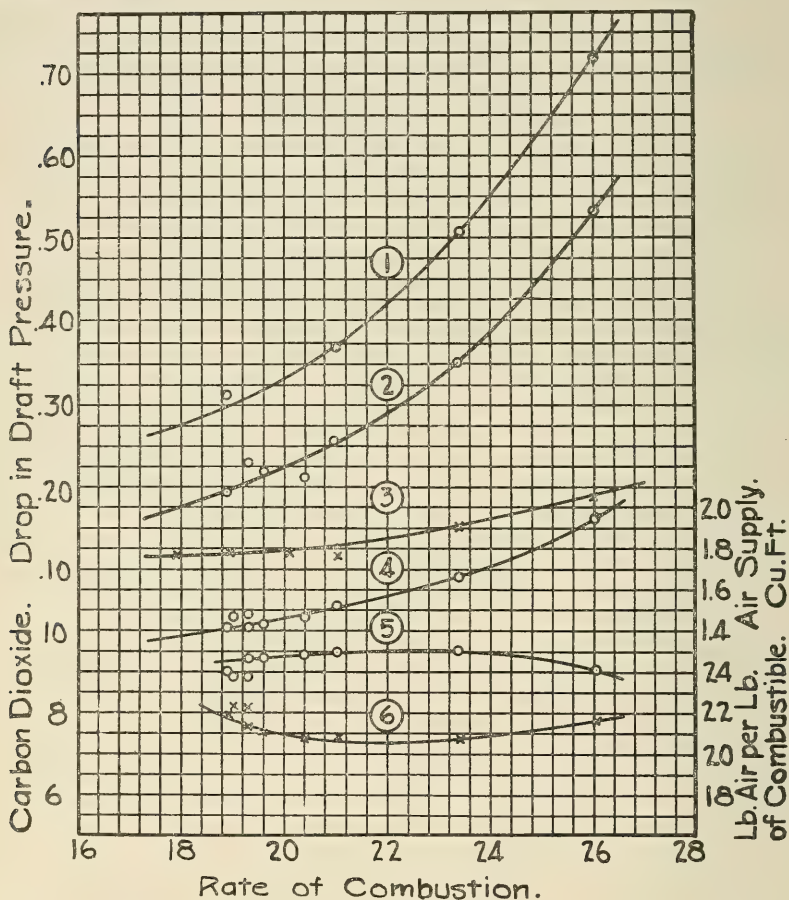


FIG. 1 TESTS OF FUELS 5.1610W AND 7.1610 —

1. Drop in draft pressure through the boiler and fuel bed, inches of water.
2. Drop in draft pressure through boiler, inches of water.
3. Drop in draft pressure through the fuel bed, inches of water.
4. Cu. ft. of air supplied per sq. ft. of grate surface per sec.
5. Per cent of carbon dioxide in the flue gases.
6. Pounds of air supplied per pound of combustible consumed.

In Fig. 1, the difference of draft pressure between the furnace and damper, designated curve 2, is plotted for tests succeeding test 30. See page 32. The points are obtained by taking the difference between columns 3 and 4, Table 36.

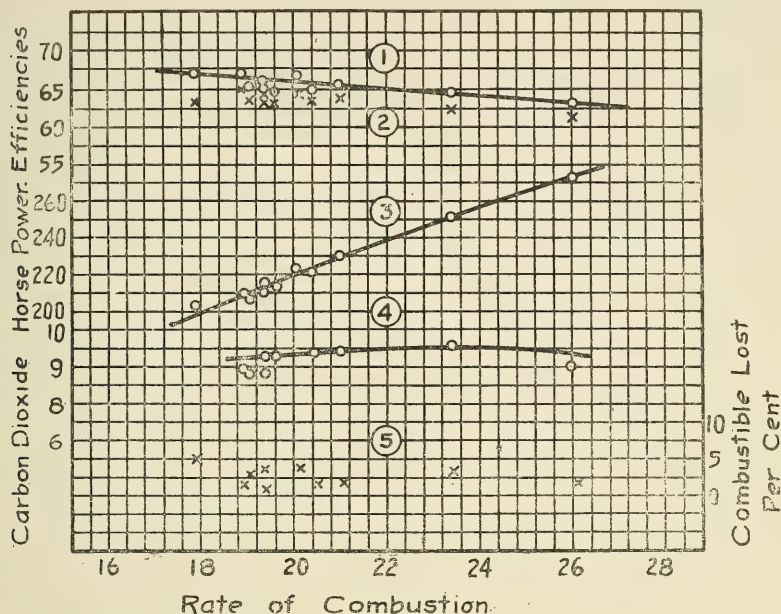


FIG. 2. TESTS OF FUELS 5.1610W AND 7.1610—

1. "Boiler and furnace" efficiency, E_2 , per cent.
2. Over-all efficiency, E_1 , per cent.
3. Horse-power developed.
4. Per cent of carbon dioxide in the flue gases.
5. Per cent of combustible lost in the "ash and refuse".

In Fig. 2, results for all tests of fuel 5.1610W and fuel 7.1610 — are plotted. It shows that the rate of evaporation or horse-power developed is directly proportional to the rate of combustion. The variation of points from the mean curves for horse-power and efficiencies shows a general relation to the variation in the per cent of carbon dioxide.

A long flame results with this fuel, but even at the higher rates there was no smoke or other evidence of incomplete combustion.

From the standpoint of uniform operation, the most satisfactory rate of combustion is in the range above 21 lb. Below this point the combustion responded too readily to slight changes in draft pressure. Clinker adhering to the ledges accumulated in smaller amounts at the higher rates.

36. *Fuel 5.1006 W*, Table 11. Normally, this fuel contains a very narrow range of intermediate sizes, although as in other well-sized coals, there is always present a proportion of sizes smaller than that of the lower screen. This is caused by the handling dur-

TABLE 11 FUEL 5.1006W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Overall Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
37	5	0.097	19.55	231.5	6.68	110.2	71.58	70.55	1.47	10.56
38	5	0.088	17.85	211.5	5.54	100.8	71.37	70.10	1.79	11.09
39	6	0.113	18.32	211.5	5.54	100.8	69.64	68.42	1.73	10.79
40	7	0.144	19.03	213.9	5.60	101.9	67.69	66.49	1.78	10.56
41	6	0.146	23.51	270.3	7.08	128.7	69.25	68.08	1.68	11.48
42	5	0.091	15.92	184.6	4.83	88.0	70.13	67.69	2.02	11.27
43	5	0.174	24.45	271.5	7.11	129.3	68.47	67.19	1.82	11.12
44	6	0.230	30.10	321.8	8.42	153.2	65.51	64.24	1.89	10.27

ing shipping. Usually, this proportion of smaller sizes does not exceed 10 per cent for washed coal similar to that from seam 7, when handled directly from the mines, though long storage may increase the amount considerably. This shipment of coal, after about six weeks' storage, was not as uniform as it was desired to have it. On the average, about 15 per cent passed through a $\frac{1}{2}$ -in. sieve, of which amount a little more than one-half was below $\frac{1}{8}$ in. The coal used in tests 42, 43 and 45, taken from the bottom of the bin, showed about 25 per cent through the $\frac{1}{2}$ -in. sieve with 10 to 12 per cent below $\frac{1}{8}$ in.

The first four tests were run at a rate of combustion giving

about normal boiler rating. Three thicknesses of fuel bed were used, the resulting efficiencies being apparently in favor of the 5 - in. fuel bed. Tests 37, 38, 39 and 40 should be compared in that respect, though because of the inequalities of size they are not entirely satisfactory. The results for test 37 do not seem to be normal with respect to the carbon dioxide per cent, but the reason is not shown in the records.

The fuel was of such a nature that the fuel bed was compact and dense in all tests; at times, especially with the 6- and 7-in. thickness, the bed became viscous, and the first serious trouble from clinkering experienced with any of the fuels tested occurred. During a period of two hours in test 40, fluxing of the ash persisted to such an extent that the fuel bed had to be broken up with the slice bar three times.

Test 42 was intended as a check on tests 37 and 38. A normal draft pressure of 0.10 in. was assigned for the test, but for the reason stated above, the resulting rate of combustion was low. Test 41 with a 6-in. fuel bed, but with higher rate of combustion, gave similar though slightly less trouble of the nature experienced during test 40.

A normal draft pressure of 0.18 in. was assigned for test 43. This was increased to 0.20 during the test with an average of 0.194 for the test. A greater increase in the rate of combustion than that obtained for test 41 was expected, but the actual increase was only 4.1 per cent with an increase in the air supply of 7.1 per cent. Thus it appears that the resistance factor for the fuel bed was increased and that the leakage of free air around the grate was greater. Less trouble was experienced in this test from clinkering than in test 41.

In test 44 under a normal draft pressure of 0.26 in., the trouble from incipient clinkering entirely disappeared. The marked drop in the boiler and furnace, and the over-all efficiency in that test is chargeable partly to excess air and low furnace effect and partly to characteristics of the boiler.

Aside from the various occurrences just stated, the furnace observers' report showed that the fuel, except at times of over-hot fuel beds, burned uniformly and required not more than average attention. As tests of the grade of coal, however, the tests are unsatisfactory. The coal of tests 37 and 38 more nearly represents the grade.

The coal burned with a long bright flame, and except in tests 43 and 44, there was no smoke. It is worthy of note that there was no indication of smoke in test 41 although there was less ex-

cess air than for test 43, a fact which indicates a more uniform distribution of the air. In test 43, Ringlemann shade No. 1 was approximated three times. In test 44, there was a faint haze of smoke throughout the test and twice for very short periods a shade corresponding to chart No. 2 was reached. For smoke averages for the tests, see Table 36.

In Fig. 3 and 4, points have been plotted from the results of this set of tests. Smooth curves have been drawn to represent the average course of results, air supply, etc., at different rates

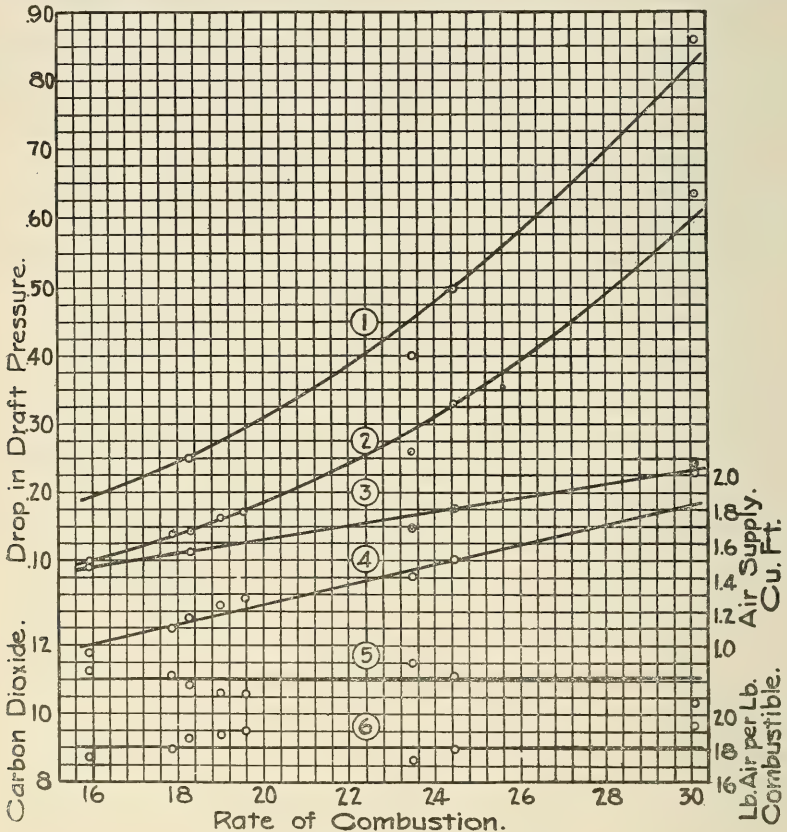


FIG. 3 TESTS OF FUEL 5, 1006 W.

1. Drop in draft pressure through the boiler and fuel bed, inches of water.
2. Drop in draft pressure through boiler, inches of water.
3. Drop in draft pressure through fuel bed, inches of water. 6 in. fuel bed.
4. Cu. ft. of air supplied per sq. ft. of grate surface per sec.
5. Per cent of carbon dioxide in the flue gases.
6. Pounds of air supplied per pound of combustible consumed.

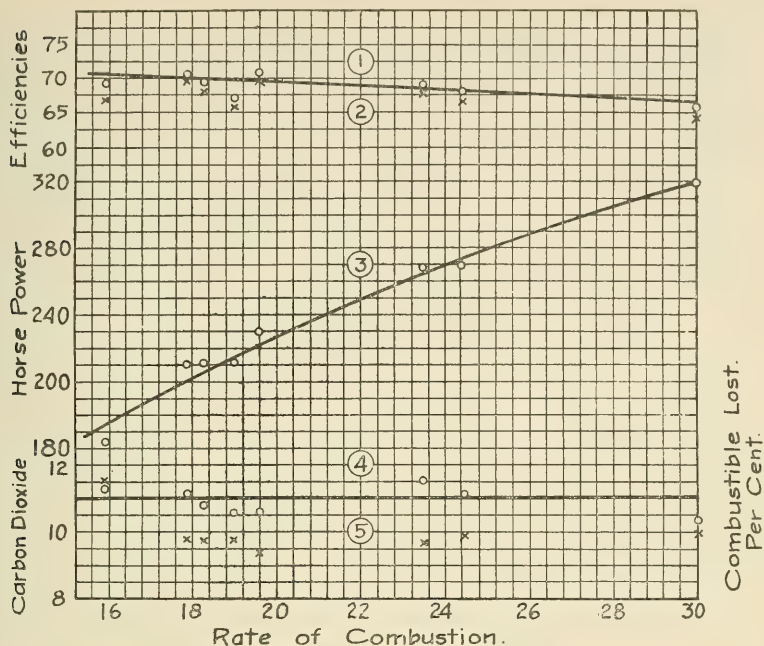


FIG. 4. TESTS OF FUEL 5.1006W

1. Over-all efficiency, E_2 per cent.
2. Over-all efficiency E_1 per cent.
3. Horse-power developed.
4. Per cent of carbon dioxide in the flue gases.
5. Per cent of combustible lost in the "ash and refuse".

of combustion. They are not strictly characteristics of a definite grade, but if each set of points for the individual tests be considered in their variation from the mean curves, much of interest will be found in their general relation to the air supply data and per cent of carbon dioxide.

37. *Fuel 6.0200 W*, Table 12.—Both as to chemical composition and commercial grade, this fuel is similar to the fuel 5.0200W used in the tests of Table 6. At the time of testing, it had been in storage for about 30 days and had dried out somewhat.

Tests 45 and 46 were made with the coal in that condition, the water content being approximately 14 per cent. The tests offer an opportunity of observing the effect of the absence of wetness. In order to take account of the dry condition, the normal draft pressure assigned for the 4-in. bed, test 45, was 0.23 in., 0.29 in. pressure having proved best for the wet coal in test 17. As a result of the dryness, about 40 per cent of the fuel fell through the grate. This was shovelled back into the hopper without wetting. The result was a thin and continually broken fuel bed,

TABLE 12 FUEL 6.0200W

Test No	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combu-tible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
45	4	0.165	13.35	115.5	3.02	55.0	53.36	48.86	8.39	4.62
46	6	0.313	15.71	131.9	3.45	63.1	52.83	50.44	4.53	4.88
47	6	0.414	16.62	151.4	3.96	72.1	55.86	54.80	1.90	5.53
48	6	0.363	16.81	165.5	4.33	78.8	60.41	58.10	3.78	5.98
49	6	0.303	13.27	121.1	3.17	57.7	55.92	53.02	5.16	5.11
50	5	0.305	15.86	155.2	4.06	73.9	60.56	57.29	5.36	6.04
51	5	0.346	16.28	159.1	4.16	75.8	60.30	57.86	4.02	5.87
52	5	0.364	17.80	175.5	4.59	83.6	60.70	58.60	3.44	6.20

requiring an excessive amount of attention. Poor results generally were shown, and it was with very great difficulty that even fairly good starting and closing conditions for the test were obtained.

Test 46 gave but slightly less trouble. An increased rate of combustion was obtained, but the fuel bed was continually broken and the furnace temperature reduced. These tests are sufficient to show that dryness is not one of the best conditions for fine coal in connection with the chain grate. This is well understood in practice, but perhaps the effect on the efficiency is not so well understood.

During the remainder of the tests of this grade, the coal was sprayed and mixed, the weight of the coal being taken after spraying. The drippings were also sprayed before refiring. Spraying the coal reduced the drippings to about 20 per cent of the coal fired.

The results for tests 47 to 52 with some allowance, perhaps 1.5 per cent variation in efficiency, Item 72.1, due to the difficulty of obtaining agreement in starting and closing conditions for the fuel bed, may fairly be considered as characteristic of the fuel and the grate, when given the best possible attention. Reference to Table 40 will show how uniform the conditions of attendance

were. In all of these tests, holes in the fire were checked at their incipency, and the fuel was frequently pushed against the ledge plates.

The furnace observers' report showed the conditions of test 48 to be the most satisfactory for the 6-in. gate opening from the standpoint of operation. For the 5-in. gate opening, the conditions of test 50 gave the least trouble in operation and those of test 52 the most. The rate of combustion and horse-power obtained in test 52 are believed, beyond doubt, to have been the maximum ones obtainable with this particular shipment of coal; the fuel bed was constantly on the point of breaking and considerable care had to be exercised to keep it in good condition.

The dependence of the "boiler and furnace" efficiency upon the temperature of combustion as indicated by the relative percentage of carbon dioxide in the flue gases and the amount of excess air, is plainly shown in these tests. If one will compare the rate of combustion and the quantity of air used in these eight tests, see page 72, an idea will be gained of the uncertainty of the amount of excess air with these fine-sized coals.

Fig. 5 shows the peculiarities of this grade of coal. The maximum rate of combustion, which is between 17 and 18 pounds of combustible per square foot of grate surface per hour, is reached when the volume of air supply is about 1.9 to 2.0 cu. ft. per sq. ft. of grate surface per second. The maximum rate for the 5-in. depth of fuel bed is not shown by the curve, though as stated above, the fuel bed in test 52 in which highest rate was obtained, was continually on the point of breaking even under great care in manipulation. In this test the air was more evenly distributed than in any of the eight tests made. In fact, better distribution of the air supply through the fuel bed and less leakage around the grate seems to be a characteristic of the 5-in. fuel bed for fine sizes. The comparison is shown in the set of curves numbered 2. The relation of the rate of combustion to the draft pressure on the fuel bed, third set of curves, is shown to be linear as long as the fuel bed can be kept in good condition.

In general, it may be said that with especial attention to the operation of the grate and the care of the fuel bed, "boiler and furnace" efficiencies of 56 to 61 per cent and over-all efficiencies from 53 to 59 per cent may be obtained, coincident with 3.2 to

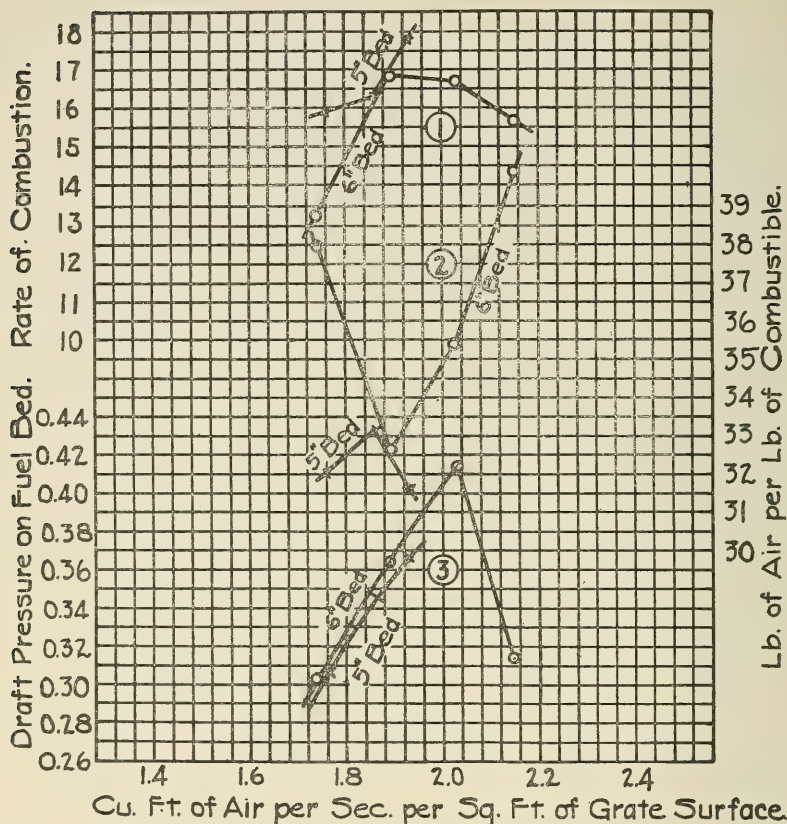


FIG. 5. TESTS OF FUEL 6.0200

1. Rate of combustion, (pounds of combustion consumed per sq. ft. of grate surface per hr).

2. Pounds of air supplied per pound of combustible consumed.

3. Drop in draft pressure through the fuel bed, inches of water.

4.6 horse-power developed per sq. ft. of grate surface per hour.

38. *Fuel 4.0300W*, Table 13—Coal of this grade, passing a $\frac{3}{8}$ -in. screen, is known as washed "duff" at the washery where it is prepared. It is sometimes marketed under that name though it is of larger size than the No. 5 coals of Tables 6 and 12.

Both the sulphur and ash content in this coal were higher than in the No. 5 coal tested. The volatile matter was about 6 per cent greater. One carload of about 24 tons was available, so that in addition to a preliminary test, not reported, but four tests were obtained.

For test 53 a normal draft pressure of 0.34 in. was assigned. The average of the draft pressure reading for the test was 0.336 as shown, and 194.8 H. P.

TABLE 13 FUEL 4.0300W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
53	5	0.339	20.45	196.5	5.15	93.6	59.73	55.88	6.51	6.56
54	5	0.298	16.81	163.8	4.29	78.0	60.98	57.30	6.05	6.16
55	5	0.367	20.71	200.1	5.14	95.3	60.15	56.68	5.79	6.58
56	5	0.381	21.70	210.4	5.51	100.2	60.73	56.76	6.50	6.90

A lower draft pressure was tried for test 54, and resulted in evaporation with no change in efficiency. A normal draft pressure of 0.38 in. was assigned for test No. 55 and 0.40 in. for test No. 56. Considerable trouble was experienced in all of the tests from coal falling through the grate, but less attention was required in keeping the fuel in good condition, than for the No. 5 coal.

In all of the tests, the coal ignited well under the arch and burned more freely and evenly over the grate than the No. 5 coal. The flame was short on account of the large excess of air and no smoke could possibly result. For the same reason no clinker was formed. Test No. 53 required the least attention to the operation of the grate while test No. 56 required the most attention.

It is possible that slightly increased rate of combustion could have been obtained, but at 0.42 inches normal draft pressure there was a serious tendency for holes to form, due to the lifting force of the draft, the light fuel particles dancing about in the same manner as in the case of the No. 5 coal.

The 5-in gate opening was used for this fuel, to agree with the best conditions found for the No. 5 coal.

For the four tests, an average of about 20 per cent of fine coal fell through the grate to the drip plate, and the fuel bed was probably more nearly of a depth represented by a 4-in. fuel bed

of larger-sized coal. Some of the characteristics noted in connection with the fuels of Tables 6 and 12 are noticeable, but the fuel is more even and responds to the draft better. There is at the same time greater uniformity in the relation of the rate of combustion to the horse-power developed. As with the No. 5 coal, the tendency here is toward less excess of air at the maximum rate of combustion, though the fuel bed showed an increased tendency to cake as the excess air was reduced. The results with this fuel are shown graphically in Fig. 6 and 7.

Fig. 6 shows the draft pressure and air supply, plotted against

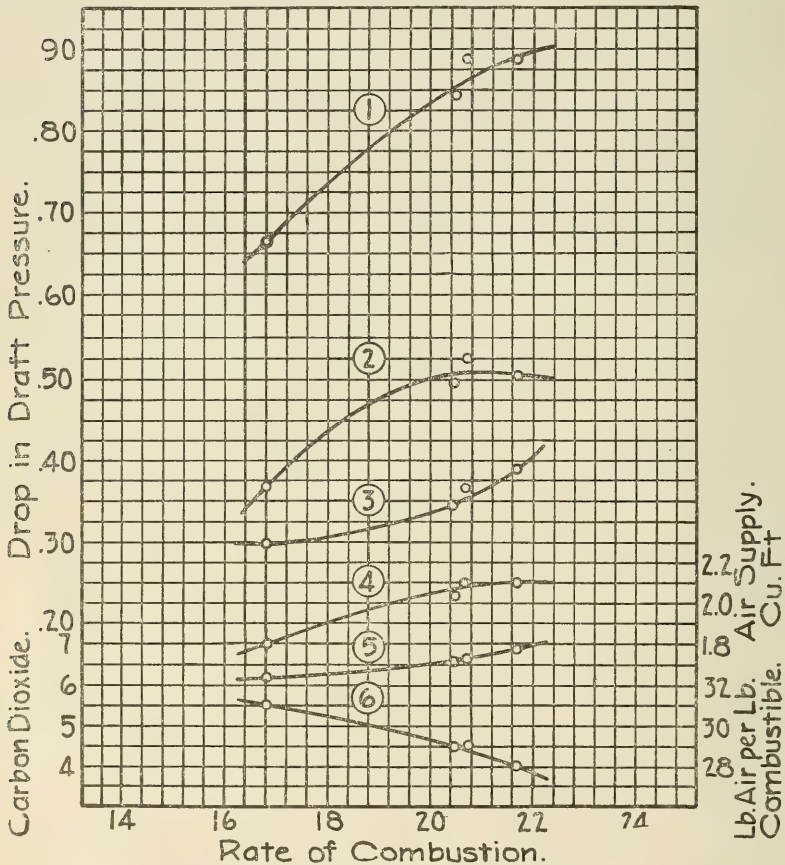


FIG. 6 TESTS OF FUEL 4.0300 W.

1. Drop in draft pressure through the boiler and fuel bed, inches of water
2. Drop in draft pressure through boiler, inches of water.
3. Drop in draft pressure through the fuel bed, inches of water. 5 in. fuel bed.
4. Cu. ft. of air supplied per sq. ft. of grate surface per sec.
5. Per cent of carbon dioxide in the flue gases.
6. Pounds of air supplied per pound of combustible consumed.

the rate of combustion. The curves are characteristic of what may be expected of this fuel. They are not to be considered, however, as showing fixed relations, for, at rates of combustion between 20 to 22, the latter being about the maximum possible rate for the grade experimented with, considerable variation occurs if the fuel bed is not kept in good condition. It will be observed that the rate of combustion does not have the same apparent proportionality to the draft pressure on the fuel bed as in preceding fuels, even under the advantage of increased utilization of the air at the higher rates. Comparing curves 3 and 6, the drop in resistance or friction within the boiler passes (upper portion of curve 2) is due, of course, to the drop in the air supply curve. The deviations of the points for test No. 56 from the mean curves are due to greater leakage.

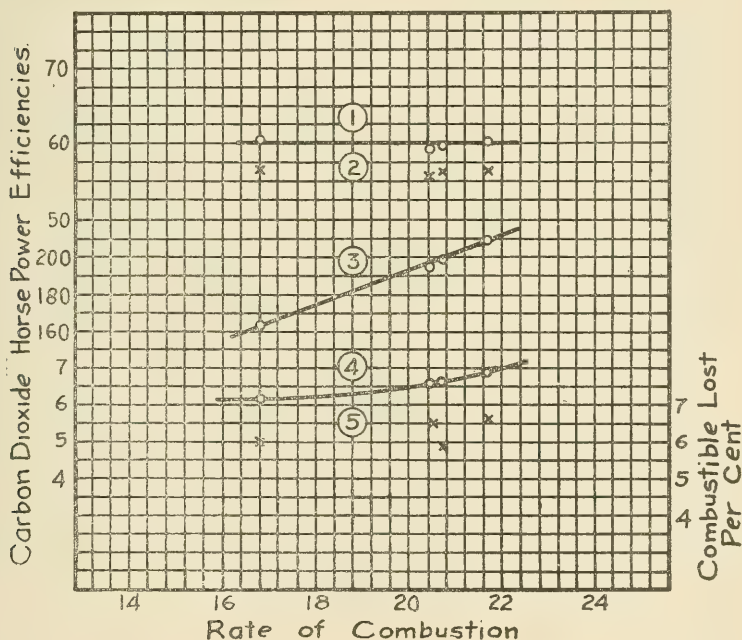


FIG. 7. TESTS OF FUEL 4.0300W

1. "Boiler and furnace" efficiency, E_2 , per cent.
2. Over-all efficiency, E_1 per cent.
3. Horse-power developed.
4. Per cent of carbon dioxide in the flue gases.
5. Per cent of combustible lost in the "ash and refuse".

Fig. 7 shows a slight improvement in evaporation for increasing rates of combustion.

39. *Fuel 4.0703 W*, Table 14.—The two series of tests made with this coal, it is believed, give a means of directly comparing the effect of differences in the furnace control. How closely, how-

TABLE 14 FUEL 4.0703W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
1	6	0.195	25.24	258.9	6.78	123.3	62.78	58.19	7.38	*10.36
2	5	0.157	24.53	264.6	6.93	126.0	65.96	63.96	3.03	* 8.77
3	4	0.116	20.52	214.3	5.61	102.0	63.94	61.34	4.05	*10.26
4	7	0.213	25.79	270.1	7.07	128.6	63.90	61.94	3.02	* 8.86
5	4	0.115	23.90	260.7	6.82	124.2	66.79	64.98	3.78	* 7.82
57	5	0.132	20.71	240.7	6.30	114.6	71.88	69.85	2.90	11.08
58	5	0.118	20.68	241.2	6.31	114.9	70.13	70.40	1.53	11.03
59	5	0.096	15.73	182.9	4.79	87.1	71.43	69.23	3.05	12.50
60	5	0.111	18.27	214.8	5.62	102.3	72.36	70.98	1.94	11.26
61	5	0.137	20.10	230.8	6.04	110.0	70.71	69.21	2.14	10.98
62	5	0.174	25.79	295.2	7.73	140.5	71.14	69.68	2.00	10.93
63	5	0.161	24.55	283.1	7.41	134.8	71.14	69.66	2.07	11.18
64	5	0.058	12.33	146.8	3.84	69.9	72.95	71.65	1.80	12.55

*See page 117.

ever, the two series may be compared in this respect can not be stated. The two sets were made some months apart and no figures are available for the radiation and conduction losses for the earlier tests. See page 53.

In tests 1 to 5, the fuel was not manipulated in any manner and irregularities consequently developed. In the first series, considerable effort was made to keep the fuel bed of standard lengths, but in all of the tests previous to test 26 it was not wholly successful. Otherwise all of the tests were conducted with the same care. Though the unreliability of the gas samples for tests 1 to 5 do not permit an estimation of the amount of excess air nor permit of the estimation of radiation and conduction losses, it is still apparent, from the percentage obtained that the difference in efficiency for the two series was due largely to excess of free air entering the furnace along the ledges and through thin parts of the fuel bed.

The control conditions for tests 57 to 64 differed in no par-

ticular from the standard conditions adopted for tests 21 to 64. As might be expected, this size of fuel from the standpoint of operation is an exceptionally favorable fuel for the chain grate, and with a little care there is no reason why equally good results may not be obtained in regular practice. Some trouble from adhering clinker along the ledges was experienced in each of the tests, due to a high fuel temperature and diminished leakage of cold air. In tests 1 to 5, no clinker was formed along the ledges since the fuel bed was not so hot and the continual stream of cold air between the grate and ledge prevented its formation. This

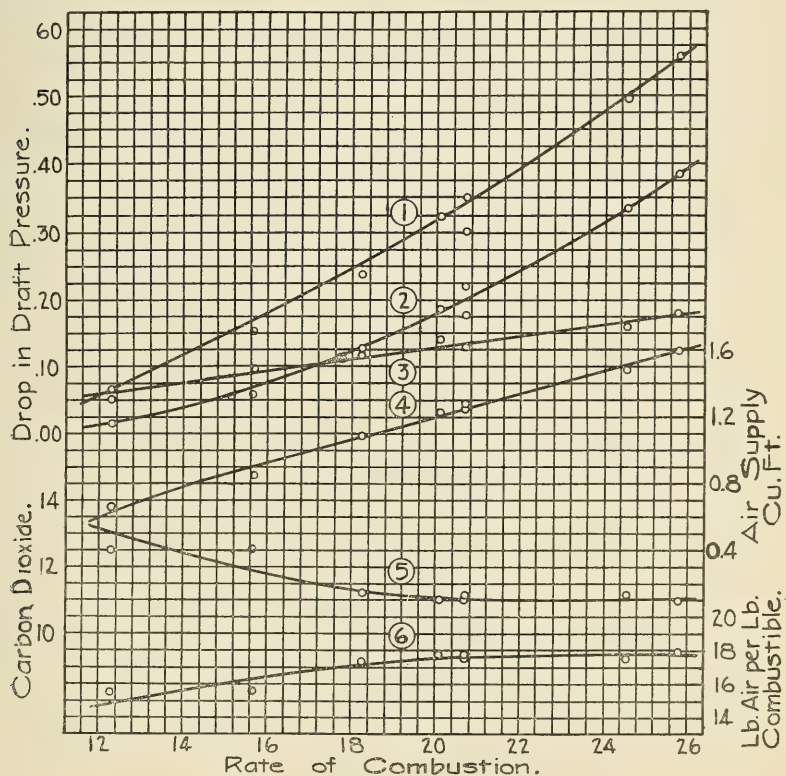


FIG. 8 TESTS OF FUEL 4.0703 W.

1. Drop in draft pressure through the boiler and fuel bed, inches of water.
2. Drop in draft pressure through boiler, inches of water.
3. Drop in draft pressure through the fuel bed, inches of water. 5 in. fuel bed.
4. Cu. ft. of air supplied per sq. ft. of grate surface per sec.
5. Per cent of carbon dioxide in the flue gases.
6. Pounds of air supplied per pound of combustible consumed.

fuel tested the combustion chamber "capacity to consume volatile matter". The flame extended through the combustion chamber and among the tubes in all the tests. Comparing the shade of smoke produced, column 12, Table 36, with the rate of combustion and the amount of air supply, columns 5 and 12, Table 14, it will be seen that the conditions tending to produce smoke depend more upon the proportion of air supplied than upon the rate of combustion. The introduction of a few mixing piers either upon the bridge wall or in the combustion chamber would, of course, result in complete combustion even with considerably reduced excess of air. With the combustion chamber and furnace as they are now, a slightly greater proportion of air is necessary to entirely prevent smoke with this fuel than is needed for the fuel from seam 7 in Williamson county. See Table 11. However, it is not possible to conclude from the evidence of the few tests of these coals available, whether any fundamental difference exists in this respect. The principal point to be noted is the absence

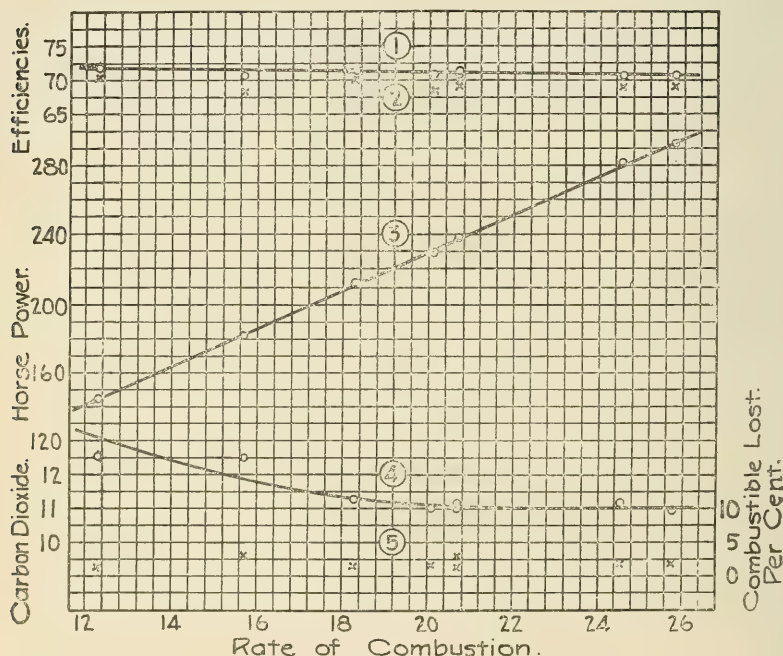


FIG. 9. TEST OF FUEL 4.0703

1. "Boiler and furnace" efficiency, E_2 , per cent.
2. Over-all efficiency, E_1 , per cent.
3. Horse-power developed.
4. Per cent of carbon dioxide in the flue gases.
5. Per cent of combustible lost in the "ash and refuse".

of any pronounced effect of high rates of combustion in producing smoke with a high volatile coal even though the excess air is extremely low.

In Fig. 8, the mean curves show the general relation of the air supply and draft for this fuel (tests 57 to 64) and in Fig. 9 is shown the corresponding evaporative performance.

Aside from the relation shown for this fuel, the curves are of interest from the fact that a wide range of combustion under uniform conditions is shown. The general remarks made in connection with the curves previously noted, apply to these curves as well and much is to be derived from a general study of the relative deviation of the plotted points from the mean curves drawn.

The nearly constant efficiency shown by the curves is of interest. At the low rates of combustion, the excess air was relatively small, as is indicated by the carbon dioxide points and the calculated points of curve 6. Consequently the furnace effect was proportionately higher. That this does not result in an upward flexure of the efficiency curves, is due to increased proportion of the radiation and conduction losses, as will be seen by referring to the values for those losses, Table 16.

VII. COMPARISON OF HEAT VALUES AND ECONOMY

40. Various factors affecting the economic results obtainable with a given coal have been outlined on page 22. The tabulated quantities of Table 16 embrace such of those values as are accessible in the data. For the purpose of uniformity in the fuel unit, the items are based upon the combustible. The derivation of the items is as follows:

Column 3. *Total heat of 1 lb. of combustible, B. t. u.* = Item 51.

Column 4. *Practical heat value, B. t. u.* = Column 3 less latent heat of moisture.

Column 5. *Heat delivered, B. t. u.* = Column 4 less heat lost in carbon of the "ash and refuse."

Column 6. *Furnace effect B. t. u.* = Column 5 $\div$ lb. moist gases per pound of combustible fed = Column 5 $\div$ (Column 7, Table 24 + Column 3, Table 15)

- Column 7. *Equivalent evaporation from and at 212° per lb. of combustible fed, pounds, compensated for water-back loss* = Item 70.1, referred to combustible fed.
- Column 8. *Service heat value, B. t. u., compensated for water-back loss* = Column 7 x 966.
- Column 9. *Radiation and conduction loss, B. t. u.* See p. 56.
- Column 10. *Service heat value, compensated for radiation and conduction loss.* See page 52.

The heat losses due to latent heat in the moisture from the coal and to the loss of carbon in the ash are shown in Table 15. The items of this table were computed as follows:

- Column 3. *Weight of water per lb. of combustible, pounds* = (per cent of moisture referred to combustible $\div$ 100) + (per cent of hydrogen in combustible $\div$ 100) x 9.
- Column 4. *Latent heat* = Column 3 x 965.8.
- Column 5. *Per cent of carbon in ash to combustible* = (Item 31 x item 44) $\div$ (100 — Item 42) See tables 29 and 38 for Item 31, 42 and 44.
- Column 6. *Heat in carbon lost* = Column 5 x 14600.

41. Reviewing the values set forth in Table 16, it cannot be doubted that the comparative values of two grades of fuels can be apparent only from an actual service test. It will be seen, however, that over-all test results in themselves do not lend themselves to close comparison. In the table are shown approximate values for the furnace effect and the sensible heat delivered per pound of combustible. In the definitions of those quantities, page 18, the radiation and conduction losses from the furnace have been given proper importance. It would likewise be consistent with a possible working hypothesis of steam boiler performance to base such definitions upon quantities of heat only that are delivered to the boiler at temperatures above that of the heating surfaces. However, to give such factors proper weight in the derivation of numerical values more elaboration is required than seems necessary, especially since the cause for variation in the evaporative results may be shown by simpler means. It is believed that this purpose has been sufficiently shown by the two heat quantities in the calculation of which no account has been taken of the radiation and conduction losses, and by way of supplement introducing as a separate item the values for the total radiation and conduction losses, furnace and boiler combined.

TABLE 15 HEAT LOSS DUE TO WATER FROM COAL AND TO CARBON IN ASH.

No.	Laboratory File No.	Water from Coal		Carbon Lost in Ash-pit		No.	Laboratory File No.	Water from Coal		Carbon Lost in Ash-pit	
		Weight per pound	Latent Heat in	Per cent of Combustible	B. t. u. in Carbon Lost			Weight per pound	Latent Heat in	Per cent of Combustible	B. t. u. in Carbon Lost
1	2	3	4	5	6	1	2	3	4	5	6
		Lb.	B. t. u.	P. ct.	B. t. u.			Lb.	B. t. u.	P. ct.	B. t. u.
1	21—4.0703 W	.716	691	7.38	1077	33	98—7.1610 —	.545	526	2.15	314
2	23—	.720	695	3.03	442	34	99—	.560	541	2.31	337
3	24—	.730	705	4.05	591	35	100—	.616	595	2.14	312
4	25—	.729	704	3.02	441	36	101—	.553	534	2.25	329
5	26—	.725	700	3.78	552	37	102—5.1006 W	.601	581	1.47	215
6	30—5.0602 W	.628	606	2.91	425	38	104—	.621	600	1.79	261
7	31—	.634	612	2.32	339	39	107—	.611	590	1.73	253
8	32—	.630	609	2.60	379	40	109—	.607	586	1.78	264
9	34—	.639	617	1.74	257	41	110—	.613	592	1.68	245
10	35—	.612	591	1.73	252	42	112—	.607	586	2.02	295
11	36—	.596	576	2.20	322	43	113—	.580	560	1.82	266
12	37—5.0200 W	.675	652	7.98	1165	44	114—	.576	556	1.89	276
13	39—	.655	632	6.12	890	45	115—6.0200 W	.655	633	8.39	1225
14	40—	.683	660	5.11	746	46	116—	.639	617	4.53	661
15	41—	.653	631	10.32	1507	47	117—	.765	739	1.90	277
16	42—	.709	685	10.27	1500	48	118—	.714	690	3.78	552
17	43—4.0700 W	.723	698	4.71	687	49	119—	.694	671	5.16	753
18	44—	.736	711	3.56	519	50	120—	.728	704	5.36	783
19	45—	.712	687	6.66	972	51	121—	.736	711	4.02	587
20	46—	.727	703	3.33	486	52	122—	.732	708	3.44	502
21	47—6.0402 W	.599	578	4.35	636	53	124—4.0300 W	.809	782	6.51	950
22	48—	.594	574	2.11	307	54	125—	.785	753	6.05	883
23	49—	.607	587	4.63	675	55	126—	.795	768	5.79	845
24	50—	.607	587	4.31	630	56	127—	.793	766	6.50	949
25	51—5.1610 W	.588	568	5.43	793	57	128—4.0703 W	.697	673	2.90	423
26	52—	.628	607	3.85	561	58	129—	.799	772	1.53	223
27	53—6.0402 W	.592	572	2.11	308	59	130—	.717	693	3.05	445
28	93—5.1610 W	.604	583	1.82	266	60	131—	.783	757	1.94	283
29	94—	.593	573	2.69	393	61	132—	.714	690	2.14	312
30	95—	.598	578	2.96	432	62	133—	.707	683	2.00	292
31	96—7.1610 —	.613	592	2.45	358	63	134—	.739	714	2.07	302
32	97—	.555	536	2.30	336	64	135—	.740	715	1.80	263

TABLE 16 COMPARISON OF HEAT VALUES AND ECONOMY, BASED ON
1 LB. OF COMBUSTIBLE AS FED.

No.	Laboratory File No.	Total Heat Value	Practical Heat Value	Sensible Heat Delivered	Furnace Effect	Equivalent Evaporation	Service Heat Value	Radiation and Conduction Loss	Service Heat Value, Compensated for Radiation and Conduction Loss
1	2	3	4	5	6	7	8	9	10
		B. t. u.	B. t. u.	B. t. u.	B. t. u.	Lb.	B. t. u.	B. t. u.	B. t. u.
1	21—4.0703 W	14247	13556	12479	.....	8.59	8298	.....	.....
2	23—	14273	13578	13136	.....	9.45	9130	.....	.....
3	24—	14239	13534	12943	.....	9.04	9732	.....	.....
4	25—	14295	13591	12180	.....	9.16	9848	.....	.....
5	26—	14241	13541	12989	.....	9.48	9157	.....	.....
	Average—	14259	13560	12945	.....	9.14	8833	.....	.....
6	30—5.0602 W	14483	13877	13352	.....	9.70	9369	.....	.....
7	31—	14467	13855	13516	.....	9.52	9196	.....	.....
8	32—	14468	13859	13480	.....	9.65	9322	.....	.....
9	34—	14477	13860	13603	.....	9.28	9965	.....	.....
10	35—	14465	13874	13622	.....	9.28	8965	.....	.....
11	36—	14549	13973	13651	.....	9.47	9148	.....	.....
	Average—	14468	13866	13537	.....	9.48	9161	.....	.....
12	37—5.0200 W	14348	13690	12525	.....	7.39	7139	.....	.....
13	39—	14391	13759	12867	.....	7.53	7274	.....	.....
14	40—	14368	13708	12962	.....	7.64	7380	.....	.....
15	41—	14353	13722	12215	.....	7.23	6984	.....	.....
16	42—	14341	13656	12156	.....	7.33	7080	.....	.....
	Average—	14371	13663	12535	.....	7.52	7266	.....	.....
17	43—4.0700 W	14295	13597	12910	.....	9.18	8868	.....	.....
18	44—	14340	13629	13110	.....	9.72	9389	.....	.....
19	45—	14340	13653	12881	.....	9.29	8974	.....	.....
20	46—	14384	13645	13159	.....	9.63	9302	.....	.....
	Average—	14839	13631	12965	.....	9.46	8883	.....	.....
21	47—6.0402 W	14516	13938	13303	.....	10.19	9843	.....	.....
22	48—	14630	14056	13749	.....	10.15	9708	.....	.....
23	49—	14516	13929	13254	.....	10.36	10007	.....	.....
24	50—	14469	13882	13252	.....	10.27	9920	.....	.....
27	53—	14503	13931	13623	.....	9.89	9554	.....	.....
	Average—	14527	13947	13436	.....	10.17	9806	.....	.....
25	51—5.1610 W	14653	14085	13292	.....	9.78	9447	.....	.....
26	52—	14499	13892	13331	.....	9.93	9593	.....	.....
28	93—	14509	13926	13660	599*	9.79	9458	.....	10609*
29	94—	14472	13899	13506	602*	9.67	9338	1155*	10493*
30	95—	14471	13893	13461	631	9.62	9287	1315	10602
	Average—	14521	13939	13450	631	9.76	9425	... ..	10602

*Not included in average.

TABLE 16 COMPARISON OF HEAT VALUES AND ECONOMY BASED ON
1 LB. OF COMBUSTIBLE AS FED

No.	Laboratory File No.	Total Heat Value	Practical Heat Value	Sensible Heat Delivered	Furnace Effect	Equivalent Evaporation	Service Heat Value	Radiation and Conduction Loss	Service Heat Value Compensated for Radiation and Conduction Loss
1	2	3	4	5	6	7	8	9	10
		B. t. u.	B. t. u.	B. t. u.	B. t. u.	Lb.	B. t. u.	B. t. u.	B. t. u.
31	96—7.1610 —	14573	13981	13623	618	9.71	9384	1355	10739
32	97—	14456	13920	13584	613*	9.93	9592	1078*	10668*
33	98—	14470	13944	13630	644	9.67	9343	1434	10777
34	99—	14548	14007	13670	646	9.72	9394	1347	10741
35	100—	14395	13800	13488	629*	9.40*	9086*	1317	10403*
36	101—	14436	13902	13573	617*	9.33*	9001*	1224	10225*
	Average—	14480	13792	13594	628	9.76	9428	1335	10752
37	102—5.1006 W	14427	13846	13631	696*	10.54	10179	766	10945*
38	104—	14487	13887	13626	738	10.51	10156	743	11099
39	107—	14470	13880	13627	718	10.25	9990	1202	11102
40	109—	14477	13891	13631	705	9.96	9625	1404	11029
41	110—	14487	13895	13650	761	10.21	9863	1084	10947
42	112—	14425	13839	13545	730	10.11	9764	1534	11298
43	113—	14145	13585	13319	722	9.81	9503*	1023	10526*
44	114—	14240	13684	13408	675*	9.47*	9148*	849	9907*
	Average—	14395	13813	13555	729	10.20	9915	1076	11095
45	115—6.0200 W	14145	13512	12287	314*	7.15*	6911*	652	7563*
46	116—	13920	13303	12642	324*	7.27*	7021*	903	7924*
47	117—	14233	13494	13217	366	8.07	7800	924	8724
48	118—	14229	13539	12987	401	8.56*	8267	536	8803
49	119—	14229	13558	12405	346	7.81	7545	831	8276
50	120—	14087	13383	12600	400	7.32	7072	656	7728
51	121—	14133	13422	12835	390	7.47	8180	595	8775
52	122—	14166	13458	12956	411	8.59	8302	480	8782
	Average—	14143	13458	12791	386	7.97	7861	697	8515
53	124—4.0300 W	14031	13249	12299	438	8.12	7841	605	8446
54	125—	13948	13190	12307	405	8.27	7992	442	8434
55	126—	14005	13237	12392	431	8.22	7939	595	8534
56	127—	13954	13188	12239	450	8.09	7819	586	8405
	Average—	13984	13216	12309	431	8.23	7898	557	8455
57	128—4.0703 W	14090	13417	12994	722	10.19	9843	637	10480
58	129—	14210	13438	13215	710	10.36	10003	524	10527
59	130—	14212	13419	13074	805*	10.19*	9839*	1296	11135*
60	131—	14171	13414	13131	725	10.41	10058	750	10808
61	132—	14161	13471	13159	714	10.15	9805	867	10672
62	133—	14045	13362	13070	705	10.13*	9768*	485	10253*
63	134—	14133	13419	13117	721	10.19*	9846*	504	10350*
64	135—	14229	13514	13251	817*	10.55*	10193*	1303	11496*
	Average—	14156	13444	13126	716	10.28	9927	796	10622

*Not included in average.

42. Over-all evaporative results in tests of fuels may be compared quantitatively only when the imposed operating conditions of the experiment are carefully taken into account, but the comparison will hold only when the experiments themselves have been made without variation due to losses from radiation and conduction. The present studies clearly show that it is impossible to eliminate such variations, and that some means of correction for the radiation and conduction losses must always be applied. In general, it may be stated that the evaporation depends upon

- (1) the heat content of the gas;
- (2) the heat delivered per pound of fuel;
- (3) the boiler characteristics;
- (4) radiation and conduction losses.

43. The values for the radiation and conduction losses for those tests (tests 30 to 64) for which there are data suitable for calculating a satisfactory heat balance, are given in column 9, Table 16. These values are the "unaccounted-for loss" items obtained in heat balances as usually computed. This item, which is obtained by subtracting the total heat measured from the total heat supplied, also represents the variations due to the balance between positive and negative errors of experiment. What weight the latter represents in the figures, cannot be ascertained. It seems reasonable to believe, however, that with the exception of those tests that have been questioned in the table, the sum of these errors does not exceed 1 per cent.

44. Comparison of the variation between the radiation and conduction losses shows the extent to which the service heat values have been affected. It should be especially noted that those tests conducted in the early spring are placed at the greatest disadvantage, e. g., fuels 7.1610—and 5.1610 W. In fixing upon a method of correction for these losses, an endeavor was made to arrive at some satisfactory means of correction for the variations only, such that the resulting corrected values would represent magnitudes obtainable by direct experiment under uniform conditions, but the possibility of such a course has been precluded for the want of a satisfactory datum of reference. The involved nature of the problem will be apparent if one reviews the various

factors that contribute to the magnitude of such losses.

However, for purposes of comparison, it is not essential that the values should numerically represent obtainable ones, and a compensation has been made in column 10 by adding the heat loss of column 9 directly to the obtained figures for the service heat value. This procedure, though somewhat arbitrary, represents the best possible information, since the values approximate those that would have obtained had the heat lost by radiation and conduction from the furnace remained in the gases; further, they eliminate any variations due to radiation and conduction from the boiler, and at the same time those that may have been introduced by errors in the coal or in the water items. This method of compensation is adopted on the theory that heat imparted to the gases above the temperature of the boiler heating surface is absorbed at very high efficiency.*

Since this efficiency, it is known, is not perfect, the figures thus obtained do not strictly represent a function embracing the heat quantities tabulated. Considering these as relative figures only, there appears no reason why, imposed conditions of operation being equal, they should not be comparable within 1 per cent total variation, whereas the over-all results, as is usual with such values, call for considerable latitude of judgment.

45. In bringing results for all of the tests together in Table 16, it is not intended to imply that the results for all tests are strictly comparable. They are brought together to give a survey of the results not afforded by other tables. Tests 1 to 20, as elsewhere pointed out, were made under different conditions of furnace control than were those of succeeding tests.

Values for the radiation and conduction losses were not obtained for tests 1 to 27, and hence a proper presentation of those tests is difficult. At the outset of the tests, it was expected that inasmuch as the boiler was housed in an independently heated building, variations from that source would be small. That between tests run some weeks apart the variation would be as shown was, however, not expected. Upon the disclosure of the conditions, it was at first thought that the results of tests 1 to 27 should be rejected. Careful analysis of those results, however, does not disclose marked variations within any one fuel series which can

*For the major number of tests made at St. Louis by the U. S. Geol. Survey, it was shown that between 80 and 87 per cent of the heat in the gases above steam temperature was absorbed. "A Study of Four Hundred Steaming tests" Bul. 325, U. S. G. S., p. 147.

not be approximately accounted for by other occurrences on record. For this reason and because their value for the other objects of the investigation has not been affected, they have been included in the report. Equal reliability of the results of tests 1 to 27 as representing the conditions that existed is not questioned. The value of these tests as a basis for comparison of the relation of grade to economy is affected, however, for the reasons given. If the tests serve no further purpose in the present connection than to emphasize the importance of reliable flue gas data in experimental boiler and furnace work, the prominence given them will not be without value.

46. The averages shown for the results of each fuel series give a hasty review of the results. In making them, values for tests run at relatively high or low horse-power or rates of combustion have been excluded, as have likewise certain other values which preceding analyses have shown to be in question.

For purposes of more accurate comparison, these averages are supplemented by Table 17. The tests compared therein with one exception, test 52, fuel 6.0200W, represent tests at approximately 210 H. P., and are tests selected especially because of their uniform furnace operation and conditions. For fuel 6.0200 W, 210 H. P., was not obtainable. The items of the table are compiled from Table 16. The ratios at the lower part of the table are taken with respect to the items for test 60, fuel 4.0703 W.

47. *Size of grade and air proportion.*—The relation of the comparable values of column 8, Table 17, to the various heat quantities has been discussed at length. It is also important to look upon the variation of value from the relationship of size and air proportion. Keeping in mind the minor modifications introduced by variations in the heat delivered per pound of fuel, the following is of interest.

48. Air enters the furnace through the active fuel bed and through leakage points outside of the fuel bed. With any constant draft pressure, the relative proportion of the total air supply entering through each source of entrance is proportional to the separate resistances of these sources. The resistance at entrance points outside the fuel bed is practically constant, but the resistance of the fuel bed (neglecting other modifying factors for the present) depends upon the sizes of the interstices between the coal particles. Thus the leakage relative to the total air

TABLE 17 HEAT VALUES AND ECONOMY—BASED ON COMBUSTIBLE AS FED (SELECTED TESTS)

	No.	Fuel	Total Heat Value	Practical Heat Value	Sensible Heat Delivered	Furnace Effect	Service Heat Value. Compensated for Radiation and Conduction Losses
1	2	3	4	5	6	7	8
Heat Quantities	30	5.1610 W	14471	13893	13461	631	10602
	31	7.1610 —	14456	13920	13584	613	10739
	38	5.1006 W	14487	13887	13626	738	11099
	52	6.0200 W	14166	13458	12956	411	8782
	56	4.0300 W	13954	13188	12239	450	8405
	60	4.0703 W	14171	13414	13131	725	10808
Ratios	30	5.1610 W	1.021	1.036	1.035	0.870	0.981
	31	7.1610 —	1.020	1.038	1.035	0.846	0.994
	38	5.1006 W	1.022	1.036	1.038	1.018	1.039
	52	6.0200 W	1.000	1.004	0.987	0.567	0.813
	56	4.0300 W	0.984	0.983	0.932	0.621	0.778
	60	4.0703 W	1.000	1.000	1.000	1.000	1.000

increases as the compactness of the fuel bed increases, and in increasing proportion as it becomes necessary to increase further the draft pressure to give the same rate of combustion or horse-power.

49. The size of the interstices between the coal particles increases with the size of the coal particles, consequently with large grades of uniform coal a large proportion of the total air passes through the fuel bed. As the interstices are further increased, however, a condition is reached where a part of the air may pass through the fuel bed without coming into contact with either gaseous or solid combustible. Thus the fuel bed itself becomes an entrance for excess air. Between the large size, therefore, with excess air entering the furnace through the fuel bed, and perhaps by leakage as well, (some excess is needed with volatile coals for the combustion of the gasified hydrocarbons), and fine sizes with a large proportion of leakage, a size will be found for which a minimum excess occurs. This general consideration would apply more strictly to a non-clinkering and free-burning

coal, except for very fine sizes. Clinkering, caking, and with fine sizes, the formation of craters in the fuel bed, modify the conditions.

50. Ash—It is held, hypothetically, that the presence of ash particles in the fuel bed decreases the chance of the air coming in contact with the solid coal substance, and, depth of fuel bed constant, that the proportion of excess air should increase with increased percentage of ash. Analyses of 286 tests at St. Louis*, however, do not show that this is true in connection with the *plain* grate for ash percentages below 16 per cent, but it was shown that clinkering of the ash is of more serious consequence because of obstruction of the grate. The extent and seriousness of clinkering depend upon the fluxing properties of the ash, the temperature of the fuel bed and the quantity of ash present. Parenthetically, it should be said that the mere presence of ash in quantity does not induce clinkering; in fact, ash which fuses in a hot fuel bed may, by its presence in large amounts, operate to prevent clinkering by inducing excess air cooling of the fuel bed and furnace.

51. Tests with the chain grate stoker, by Mr. W. L. Abbott†, to determine the effect of varying percentages of ashpit refuse added to No. 4 washed coal, show the following results for percentages of ash below 25 per cent.

TABLE 18

Per cent of Ash in Dry Coal	Efficiency
9	59.0
16	57.0
20	61.5
24	56.0
24	57.0

For percentages of ash above 30 per cent, Mr. Abbott's results varied widely, as might be expected. Results for the lower percentages show no greater variations than are usual to over-all results.

52. The percentage of ash for the tests of Table 17 range from 9 to 16 per cent, dry coal basis, and it appears from the results just quoted that except for tests of fuel 5.1006 W, in which serious clinkering occurred, no important variations are to be ascribed to ash, but that the excess air quantities, (see p. 80), under the test conditions, are to be considered as characteristics of the grate

*Bul. U. S. G. S. 190, p. 39.

†Jour. Wester Soc. Engrs. Vol. 11, p. 529.

sizes. This would in fact be true under any consideration since the percentages of ash in washed grades have a close relation to the grade size.

In the paper quoted above, Mr. Abbott has shown a similar and remarkable relationship for specially prepared *unwashed* sizes based, however, upon size and *efficiency*.

VIII. EFFECT OF DIFFERENT THICKNESSES OF FUEL BED

53. In connection with the detailed statement concerning results set forth in Tables 5 to 14, a cursory examination of the effect of different thicknesses of fuel bed has been made. It is intended here to summarize the general conclusions in that respect presented by the data. Aside from a general contribution to the data on each grade, two points of interest in respect to the thickness of fuel bed have been under investigation.

(a) The first of these was to determine whether any difference in the amount of combustible matter in the ash-pit refuse would result for different thicknesses of fuel bed.

(b) The second point of interest relates to the determination of whether or not a different economy would result for different thicknesses.

54. *Loss of Fuel in the "Ash and Refuse".*—Relative to the first question, it was thought that thick fuel beds, with their higher interior temperature and consequent higher temperature of the layer of ash beneath, together with the proportionately greater quantity of air which must necessarily pass through each unit area of the ash bed, would result in smaller ashpit loss; that is, according to the accepted notion of combustion and of the protecting effect of ash in quantity, the chances of air coming into contact with the imbedded fuel particles are in proportion to the product of the rate of air flow and the time that the ash remains upon the grate.

55. In Table 19, the averages of the available data for each thickness of fuel bed are given for the several grades. Compar-

TABLE 19 RELATION OF LOSS OF FUEL IN THE "ASH AND REFUSE" TO THE THICKNESS OF THE FUEL BED

Thickness of the Fuel Bed, Inches	Loss of Fuel, per cent of Total Combustible									
	Fuel 5.0602 W	Fuel 5.0200 W	Fuel 4.0700 W	Fuel 6.0402 W	Fuel 5.1610 W	Fuel 7.1610 —	Fuel 5.1006 W	Fuel 6.0200 W	Fuel 4.0300 W	Fuel 4.0703 W
1	2	3	4	5	6	7	8	9	10	11
4	2.91	10.29	6.66	4.31	.....	.....	.....	8.39	.....	.....
5	2.60	7.98	4.13	4.63	2.96	2.45	1.76	4.27	6.21	2.18
6	2.20	5.61	3.33	3.26	2.69b	2.25	1.78	3.84	.....	.....
7	1.73	.....	.....	3.01	1.82	2.15	1.78	.....	.....	.....

ing these results with the conditions of fuel bed area, (columns 3, 4, 5 and 6, Table 40), it will be seen that the variations in the latter had a minor effect upon the ash-pit loss. Comparing the ash-pit loss with the grate travel (column 12, Table 40), it appears that the latter *per se*, is not the factor in determining the percentage of loss. This is verified by the fact that the slight variations in the loss for the same grade and the same thickness of fuel bed show no relation to the difference in rates of combustion.

56. The explanation of the variation of loss due to difference in thickness for one grade, it is believed, agrees with the premise which led to the carrying out of the experiments.

Inspection of the difference in loss with different grades for the same thickness of fuel bed shows that there is a general coincidence between increased loss and the increased ash in the coal, and likewise the amount of excess air used in burning the coal, factors which affect the depth and the temperature of the ash layer. That these two factors determine the difference between losses for different grades, when the variations due to irregularities of operation are minimized, seems reasonable, but the effects can not be shown separately in the data available.

57. *Effect of Thickness of Fuel Bed upon Economy.*—Coke, just as anthracite coal, requires a moderately thick fuel bed in order

b. Tests 25 and 26 not included.

that the air supplied through the bed may be satisfactorily utilized. For bituminous coal, on the other hand, because of the volatile matter gasified in the voids between the coal particles, a much thinner fuel bed suffices. In the combustion process upon mechanical stoker grates, conditions are peculiar; at the feed end of the grate bituminous coal is under combustion with a deficiency of air, while over a greater or less portion of the grate, coke is under combustion with a thin fuel bed, and therefore with the possibility (depending upon the size of the fuel and the degree of caking which has occurred) of a greater or less excess of air. Thus the relative depths of fuel along the grate from the feed gate to the ashpit are the reverse of what would be considered good practice in hand firing. It has usually been assumed that thicker fuel beds for the chain grate stoker result in less excess of air and better economy. To what extent this would affect the choice of thickness of fuel bed in the comparison to be made of grades, became naturally a question for investigation.

58. Two series of experiments with the chain grate by W. L. Abbott*, one with No. 5 washed coal at a depth of fuel bed from 4.5 to 8.5 inches, and one with washed screenings at depths from 4 to 12 inches, resulted in minor variations only in the efficiency E₂. In explaining his results, Mr. Abbott concluded that "under these conditions, a thin fire increases the loss due to excess of air, but decreases that due to smoke and incomplete combustion. On the other hand, a thick fire reduces the excess of air, but increases the smoke and escaping combustible gas." The experiments were made in connection with a Babcock and Wilcox boiler; and to the length of the vertical pass, 14 tubes high, Mr. Abbott speculatively attributed some of the influence toward constancy of results.

59. With the equipment used in the experiments of the present paper, no smoke results under proper operation at any thickness of fuel bed, so that previous opinion seemed to confirm the expectation of a difference in results under such conditions. In outlining the experiments, thicknesses of fuel bed to be used were confined to those usual in practice. In the first few experiments, it became apparent that any differences in results due to different thicknesses of fuel bed were small, and it appeared extremely doubtful whether they could be shown upon the basis of over-all

* Jour. Western Soc. of Engineers, Vol. 11 p. 529.

results. The results up to test 27, due to the failure to obtain satisfactory flue gas samples, gave no indication as to how much the resulting efficiencies might be affected by radiation losses; consequently, tests 28 to 34, 37 to 40 and 45 to 52, were intended to be suitable for closer comparison.

60. All tests intended for comparison in this respect were to be run with a developed horse-power of as nearly boiler rating as possible; but in order that they might be consistent with the general plan to maintain as nearly an even rate of combustion as possible throughout any one test, and thus be available for other comparisons, they vary slightly above or below, depending largely upon the closeness with which the draft requirements were pre-estimated. For the smaller sizes of fuel, however, the problem as previously noted resolved itself into a determination of the most favorable conditions for maximum results and the results obtained are generally not only below 210 horse-power but themselves vary considerably.

Other desirable features in order that the results should be free from modifications in the air supply not due to variation in the thickness of fuel bed, are:

- (a) Uniformity of the fuel.
- (b) Uniform area of the fuel bed.
- (c) Uniform conditions of the fuel bed.
- (d) Uniformity as to clinkering or caking.
- (e) Leakage influenced normally in respect to draft pressure.

61. Taking these desiderata into account, and guided by the exacting criticisms of the data that have been made in connection with the discussions of Table 5 to 14, a number of tests have been rejected. Those which conform more closely are tabulated in Tables 20 and 21. The following tests have been used in these tables:

- Fuel 5.0200W,—tests 12, 13, 14, 15 and 16.
- Fuel 4.0700W,—tests 17, 18, 19 and 20.
- Fuel 6.0402W,—tests 21, 22, 23 and 24.
- Fuel 5.1610W,—tests 28, 29 and 30.
- Fuel 7.1610—,—tests 31, 33 and 34.
- Fuel 6.0200W,—tests 48, 50 and 51.
- Fuel 5.1006W,—tests 38, 39 and 40.

TABLE 20 RELATION OF EFFICIENCY TO THE THICKNESS OF THE FUEL BED

Thickness of Fuel Bed, inches	Fuel 5.0200 W			Fuel 4.0700 W			Fuel 6.0402 W			Fuel 5.1610 W		
	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	Boiler and Furnace" Efficiency, E_2
1	2	3	4	5	6	7	8	9	10	11	12	13
4	49.56	10.29	55.32	64.69	6.66	67.04	68.56	4.31	71.65	.....	.....	.....
5	49.76	7.98	54.08	63.82	4.13	66.55	68.90	4.63	72.24	64.18	2.96	66.14
6	51.55	5.61	54.65	64.68	3.33	66.80	67.84	4.35	70.92	64.52	2.69	66.28
7	.....	.....	.....	.....	.....	.....	66.98	3.01	68.46	65.19	1.82	66.38

TABLE 21 RELATION OF EFFICIENCY TO THE THICKNESS OF THE FUEL BED

Thickness of the Fuel Bed, inches	Fuel 7.1610—				Fuel 6.0200 W				Fuel 5.1006 W			
	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Furnace Effect	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Furnace Effect	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Furnace Effect
1	2	3	4	5	6	7	8	9	10	11	12	13
5	64.40	2.45	65.90	618	57.57	4.69	60.43	395	70.10	1.79	71.37	738
6	64.58	2.31	66.13	646	58.10	3.78	60.41	401	68.42	1.73	69.64	718
7	64.56	2.15	65.97	644	.....	.....	.....	...	68.49	1.78	67.69	705

62. The tests of fuel 5.1006W were affected by increased clinkering with increased thickness of the fuel bed. This feature seemed to be characteristic of this fuel. However, the three tests need not be given the same weight as the other tests selected. The tests of fuel 5.0602W, Table 22, may be usefully reviewed in this connection, for although the fuel bed areas were irregular as compared with the conditions for the tests of Tables 20 and 21, and although no attention was given to diminish sources of air leakage (the general efficiency was uniformly low on this account), it will be seen that the results for the different thicknesses of fuel bed are parallel to those of the closely similar grade 6.0402W. The lesser values for the 6- and 7-in. beds, as previously stated, page 25, are partly attributable to irregularity of the grate performance.

TABLE 22 FUEL 5.0602 W

Thickness of Fuel Bed inches	Over-all Efficiency E_1 Item 73.1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Effi- ciency, E_2 Item 72.1
4	64.72	2.91	66.66
5	64.42	2.60	66.16
6	61.91	2.20	64.38
7	62.00	1.73	63.09

63. The values for the furnace effect in Table 21, columns 5, 9 and 13, eliminate the variations due to radiation losses for those tests and serve as a qualitative check on the direction of the variations. For the fuel 7.1610—, the figures indicate that a decreased excess air resulted with thickened fuel bed. No difference is shown for the 5- and 6-in. fuel beds of fuel 6.0200W. For the fuel 5.1006W an increase in the excess air with thickened fuel bed is shown. Column 6, Table 24, gives directly the excess air figures for these tests. Inspection of the results for the different fuels shows, except for fuels 5.1006W and 5.0602W, a variation in the over-all efficiency E_1 of less than 2 per cent for the range of thickness tried.

64. The tendency toward decrease in ashpit loss as the fuel bed is thickened, has already been noted. Decrease in ashpit loss has its proportionate effect upon the over-all efficiency, so that the effect of different thicknesses upon the utilization of the air supply would be better shown by the efficiency E_2 .

65. The effect of radiation and conduction losses for the tests of Table 20 and for the fuel 5.0602W cannot be shown. For those tests for which values for the radiation and conduction losses have been obtained, Table 16, it will be noted that the variations in those losses are not great for tests of one grade which were run at approximately the same rate of combustion, though exception must be made for the tests of fuel 5.1006W in which various irregularities occurred. These facts may be noted by inspection and it will be seen that the conclusions based upon the selected data above, it so happens, are not modified.

66. The reason E_2 fails to show a definite increase with increase in the thickness of the fuel bed, must be explained by the facts that leakage of air otherwise than through the fuel bed proper is proportional to the draft pressure, while the total rate of air flow is approximately constant under the conditions. Compare column 6, Table 24, for the tests analyzed. Stated in other words, the resistance of the natural leakage points is more nearly constant than is the fuel bed resistance which increases with increased thickness of the fuel bed.

67. Since the variation in results due to different thicknesses of fuel bed is only of such magnitude as may result from slight irregularities in furnace control, and is smaller than those due to possible irregularities under ordinary operation, it is evident that the selection of fuel bed depth should be governed by the attention required for uniform results. The test records from the furnace observer's report show that a five-inch fuel bed is most satisfactory for the fuels below the size $1\frac{3}{4}$ to 1; for the latter size, a 6-in. fuel bed was preferred.

IX. RELATION OF GRADE TO THE RATE OF COMBUSTION AND HORSE POWER

68. In the various tabulations given elsewhere in the report, the rates of combustion and horse-power obtained as results of the experiments are included. With the exception of those grades that show a maximum rate within the limits of the experiments, there is no doubt that the grades tested should give any range in rates of combustion desirable for stationary practice, provided suitable draft capacity is available.

69. Very satisfactory means are at hand for a comparison of the economic values of fuels, and it seems that some means of comparing rate of combustion and horse-power would be of commensurate usefulness. Obviously, such a comparison must give due consideration to draft conditions, and in any steam plant it would be most direct to compare fuels under the draft conditions prevailing. Mr. Abbott's tests show an interesting comparison of power obtained with various fuels under restricted draft conditions.

70. Numerous factors modify draft conditions, such as height and capacity of chimney, capacity of the draft fan, difference in the friction within the boilers, the capacity of the lateral flues, the number of furnaces served by each flue, the rate at which they are driven, etc. To consider all of these factors makes the question of draft conditions an extremely complicated one, so much so that all efforts of engineers to formulate a rational treatment of the subject has been unsuccessful. Empirical and approximate formulas supplemented by the judgment of the designer, are relied upon in designing draft systems, so that until more rational methods are devised, the results obtained under one set of plant conditions naturally must be looked upon as restricted in their application.

71. A satisfactory comparison of rates of combustion should eliminate all modifying factors except those of the furnace and the fuel, and the comparative figures obtained should be applicable to any condition of draft within the range of requirements of the fuels in question.

72. It is sometimes thought that a fundamental basis for comparing rates of combustion should be found in some arbitrarily chosen draft pressure, but though the knowledge of draft pressure requirements for each separate grade is invaluable for proper furnace control, a comparison of the draft pressure requirements over an extended range for several grades will show that as many relative values for rates of combustion may be selected as there are possibilities of choosing a basic draft pressure value. This is true for a comparison upon the basis of the drop in draft pressure, whether the drop for the fuel bed, or the boiler, or the two combined is considered. These complications are, of course, due to the fact that the draft pressure is never a measure of the quantity of air supply except under very special conditions.

It seems, therefore, that a logical comparison must necessarily be based upon factors that are fundamental in the actual combustion of the fuel and not upon incidental factors.

73. In the comparisons made below, the principles set forth on page 18 are made use of. It is evident that at a constant rate of air supply, the "ratio of the air used to the air supplied" is equal to the ratio (at constant rate of air supply) of the weight of fuel consumed, to the weight of fuel which it is possible to consume under complete utilization of the air supplied.

This ratio is termed here the *relative rate of combustion*.

$$\begin{aligned}\text{The relative rate} &= \frac{\text{Rate of combustion obtained}}{\text{Maximum possible rate}} \times 100 \\ &= \frac{\text{air used per pound of fuel}}{\text{air supplied per pound of fuel}} \times 100\end{aligned}$$

74. *Comparison of Rates of Combustion.* The following comparisons are based upon the principles just outlined. The values for the relative rate are those given in column 5, Table 24; the values for the volume of air supplied per second are those of column 6 of the same table. A review of the comparisons made under three (3) below will show that it is not essential that the figures for the volume of air supply exactly agree.

(1) A comparison of the larger grades upon the basis of 1.5 cu. ft. of air per sq. ft. of grate surface per second is as follows:

Test No.	Fuel	Relative Rate	Rate of Combustion (Test Data)
30	5.1610 W	55.0	19.35
34	7.1610 ---	56.3	21.02
43	5.1006 W	63.8	24.45
63	4.0703 W	64.7	24.55

(2) Comparison of three smaller grades and the fuel 7.1610— at 2 cu. ft. of air supplied per second shows:

Test No.	Fuel	Relative Rate	Rate of Combustion (Test Data)
36	7.1610 —	54.2	26.05
44	5.1006 W	58.5	30.10
56	4.0300 W	42.4	21.70
47	4.0200 W	33.2	16.62

(3) Comparisons within individual grades with respect to relative rates of combustion with various rates of air supply show:

Fuel 4.0300W

Test No.	Air Supply	Relative Rate	Rate of Combustion (Test Data)
54	1.808	37.0	16.81
53	2.036	39.3	20.45
55	2.093	39.4	20.71
56	2.095	42.4	21.70

Fuel 6.0200W

49	1.735	30.6	13.27
50	1.759	36.0	15.86
51	1.860	35.4	16.28
48	1.888	35.1	16.81
a45	1.919	28.2	13.35
52	1.933	37.2	17.80
b47	2.026	33.2	16.62
a46	2.154	29.2	15.71

a. Very dry fuel.

b. Very wet fuel.

Fuel 5.1610W

30	1.42	55.0	19.61
29	1.46 ¹	52.3 ¹	19.06
28	1.48 ¹	52.4 ¹	19.35

NOTE 1. Gas sample diluted by leak.

Fuel 7.1610—

31	1.408	55.8	19.32
32	1.423 ²	54.0 ²	18.90
33	1.466	56.2	20.44
34	1.507	56.3	21.02
35	1.664	56.9	23.40
36	1.943	54.2	26.05

NOTE 2. Gas sample diluted by leak.

Fuel 5.1006W

42	0.96	64.6	15.92
38	1.102	65.8	17.88
39	1.166	65.1	18.32
40	1.233 ³	63.0 ³	19.03
41	1.396	65.9	23.51
43	1.503	63.8	24.45
44	1.997	58.5	30.10

NOTE 3. Fuel bed clinkered badly.

Fuel 4.0703W

64	0.655	72.5	12.33
59	0.847	71.6	15.73
60	1.088	64.8	18.27
61	1.230	63.9	20.10
57	1.250	65.2	20.71
58	1.266	64.4	20.68
63	1.480	64.7	24.55
62	1.589	63.1	25.79

Inspection of these tabulations shows for the larger grades a tendency toward decreasing relative rate as the rate of air supply and the rate of combustion increase; with the fine sizes an opposite tendency is shown, but with all grades the average magnitude of the relative rate characterizes the fuel grade. This comparison it will be observed, is simply a special adaptation of the air supply data.

75. *Comparison of Horse-power.* No fundamental unit of comparison of the power obtainable with various fuels is at hand as there is in the case of the rates of combustion. However, since at constant temperature of the gases the horse-power developed is principally determined by the rate of air supply, comparison upon the basis of equal rate of air supply and the actual horse-power obtained appears to be most logical. A comparison in this manner is made below. The results, however, apply only to the 210 H. P. boiler supplied by a grate area of 38.2 sq. ft., and since actual figures and not ratios are compared, accuracy in this demands that the air supply in each case should be the same. In the comparisons made, horse-power values at rates of air supply closely agreeing in value with the rate of air supply taken as a reference datum, have been chosen and a correction has been applied in each case by multiplying the values by the ratio of the unit rate of air supply chosen to the actual rate of air-supply, the assumption being that for moderate variations in the rate of air supply and horse power, the efficiency variation would be negligible.

1. Air supply, cu. ft. per second = 1.5×38.2

Test No.	Fuel	Air Supply	H. P.	H.P. Corrected to basis of 1.5 cu. ft. of air supply
30	5.1610 W	1.421	215.3	227.0
34	7.1610 —	1.507	231.9	231.0
43	5.1006 W	1.503	271.5	270.5
63	4.0703 W	1.480	283.1	286.7

2. Air supply, cu. ft. per second = 2.0×38.2

Test No.	Fuel	Air Supply	H. P.	H.P. Corrected to basis of 2 cu. ft. of air supply
36	7.1610 —	1.943	275.0	282.9
44	5.1006 W	1.997	321.8	322.0
56	4.0300 W	2.095	210.4	201.0
47	6.0200 —	2.026	151.4	149.5

X. DRAFT AND DRAFT PRESSURE REQUIREMENTS OF THE DIFFERENT GRADES

76. Inspection of the draft pressure data given in Tables 5 to 14 and in the curves numbered 3 in Fig. 1, 3, 5, 6 and 8, will show the characteristic differences in the draft pressure requirements for various rates of combustion of different grades. The rate of increase of the drop in draft pressure through the fuel bed and grate as the rate of air supply is increased, is shown for five grades by the slopes of the curves in Fig. 10. The curves are shown to be straight lines within work-

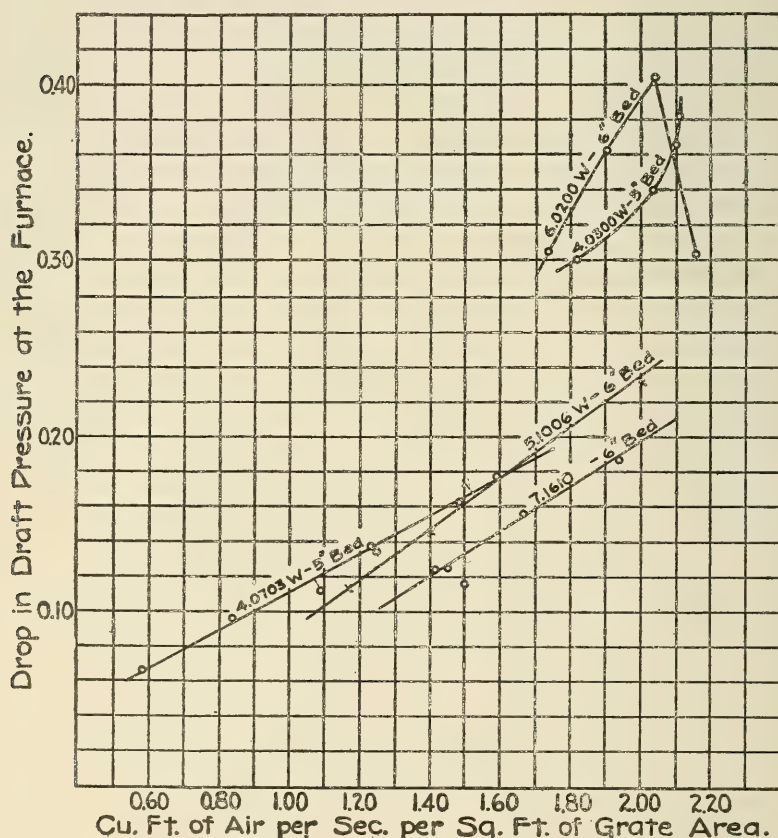


Fig. 10. Air Supply to Furnace and the Corresponding Drop in Draft Pressure.

ing range. Below the ranges shown, such curves, it is known, bend toward the horizontal. Variation from a straight line within the range of these experiments is due to an increased proportion of leakage induced by irregularities in the fuel bed or by clinkering or caking. The curve for fuel 4.0300 W shows the influence of gradually increased caking. As previously noted, the smaller grades, 6.0200 W and 4.0300 W reach a maximum respectively at about 2.0 and about 2.1 cu. ft. of air supplied per square foot of grate surface per second. The air actually passing through the fuel bed itself was, of course, in all cases less than the amounts shown.

77. *General Draft Relations.* For the purpose of showing the comparisons in Table 23, one test with a 5-in. fuel bed and at as

TABLE 23 AIR SUPPLY AND DRAFT PRESSURES FOR GRADES
TO DEVELOP THE BOILERS' RATED CAPACITY
5-inch thickness of fuel bed

Index No.	Test No.	Horse Power	Air Supply, cu. ft. of Grate per sec.	CO ₂ Per cent	Drop in Draft Pressure through			Combustible Consumed per sq. ft. of Grate Surface per hour, pounds
					Fuel and Grate inches Water	Fuel, Grate and Boiler inches Water	Boiler inches Water	
1	2	3	4	5	6	7	8	9
5.1610 W	30	215.3	1.421	9.38	0.10	0.32	0.22	19.61
7.1610—	31	216.2	1.408	9.32	0.09	0.32	0.23	19.32
5.1006 W	38	211.5	1.102	11.09	0.09	0.23	0.14	17.85
4.0703 W	60	214.8	1.088	11.26	0.11	0.24	0.13	18.27
4.0700 W	17	213.3	.....	.....	0.13	0.45	0.32	19.92
5.0602 W	8	216.3	.....	.....	0.09	0.32	0.23	19.71
6.0402 W	23	207.6	.....	.....	0.11	0.35	0.25	17.28
4.0300 W	56	210.4	2.095	6.90	0.38	0.89	0.51	21.70
6.0200 W	52	175.5	1.933	6.20	0.36	0.83	0.47	17.80

nearly boiler rating as possible, was made with each grade.

Tests 8 and 17 as elsewhere explained are not directly comparable with the tests of the remaining grades. With increased attention to the fuel bed for those tests, less air for the same horse-power would have resulted, and consequently the draft pressure drop through the boiler would have been less. With fuel 6.0200 W, 173.5 horse-power was developed. The builders' rated horse-power as previously noted was not obtainable with that fuel. Air supply figures are not calculated for

those tests for which the flue gas samples were unsatisfactory.

In these tests, as in all tests, the quantity of excess air could have been reduced by keeping the fuel slightly banked at the rear of the grate. In so operating, increased temperature of the furnace gases and corresponding decreased draft requirements throughout for the same horse-power developed would result, but with uncertain effect upon the ashpit loss and the over-all economy.

XI. AIR SUPPLY

78. In Table 24 are presented the various air supply data for tests 28 to 64. A description of the manner of taking the gas samples, upon the analyses of which computations of these items are based, is given on page 117. The items of columns 3 and 4 have been referred to the basis of one pound of combustible consumed. Multiplying them by the factor $(100-c) \div 100$ will convert them to the basis of one pound of combustible as fed, where c is the per cent of carbon in the ash and refuse referred to the combustible as fed. The ratios, columns 5 and 6 and the rate column 8 are, of course, independent of the fuel unit.

The items in the various columns were calculated as follows:

Column 3. Weight of air supplied per pound of combustible consumed,

$$= \frac{N}{.33 (CO_2 + CO)} \times \frac{C - c}{100 - c},$$

where N , CO_2 and CO denote respectively the percentages of nitrogen, carbon dioxide and carbon monoxide in the flue gases as given in Table 36, C denotes the per cent of carbon in the combustible = Item 37.1, Table 39, and c the per cent of combustible in the carbon lost in the ash and refuse. Column 5, Table 15.

Column 4. Weight of air used per pound of combustible consumed,

$$= \frac{N - 3.77 \times O}{.33 (CO_2 + CO)} \times \frac{C - c}{100 - c},$$

where O denotes the percentage of oxygen in the flue gas.

This item gives the minimum air requirement for the combustible composition consumed.

Column 5. Ratio of air used to air supplied, per cent,
 $= \text{Column 4} \div \text{Column 5}.$

It also may be obtained directly from the flue gas analysis by means of the formula,

$$\frac{\text{Air used}}{\text{Air supplied}} = \frac{N - 3.77 \times O}{N}$$

Column 6. Ratio of excess air to air used, per cent,
 $= \frac{3.77 \times O}{N - 3.77 O}$

Column 7. Weight of dry flue gases per pound of combustible fed,
 $= \frac{11 CO_2 + 8 O + 7 (CO + N)}{3 (CO_2 + CO)} \times \frac{C - c}{100}$

Column 8. Cu. ft. of standard air per sq. ft. of grate surface per sec.,
 $= (\text{Column 3} \times \text{lb. of Comb. consumed per sq. ft. of grate surface per Hr.} \times 12.39) \div 3600.$

79. The resulting air supply items of this table are extremely interesting in that they show the principal cause of variation in the economic results of the tests. The relation thereto and the relation to the rate of combustion have been discussed in the preceding pages.

TABLE 24 AIR SUPPLIED

No.	Laboratory File No.	Air per lb. of Combustible Con- sumed		Ratio of Air Used to Air Supplied, per cent	Ratio of Excess Air to Air Used, per cent	Dry Flue Gases per lb. of Combustible Fed, pounds	Cu. ft. Standard Air per sec. per sq. ft. of Grate Surface
		Lb. Supplied	Lb. Used				
1	2	3	4	5	6	7	8
28	93-5.1610 W	22.28	11.67	52.4	90.94	22.19	1.484
29	94- "	22.21	11.60	52.3	91.51	21.94	1.457
30	95- "	21.05	11.58	55.0	81.76	20.75	1.421
31	96-7.1610-	21.55	12.05	55.8	79.29	21.00	1.432
32	97- "	21.88	11.82	54.0	85.09	21.63	1.423
33	98- "	20.85	11.72	56.2	77.93	20.65	1.466
34	99- "	20.83	11.73	56.3	77.56	20.60	1.507
35	100- "	21.30	11.96	56.9	75.70	20.50	1.692
36	101- "	21.67	11.75	54.2	84.41	21.43	1.943
37	102-5.1006 W	19.00	11.96	62.9	58.82	18.99	1.278
38	104- "	17.93	11.81	65.8	51.81	17.86	1.102
39	107- "	18.50	12.05	65.1	53.52	18.38	1.166
40	109- "	18.83	11.86	63.0	58.70	18.75	1.233
41	110- "	17.25	11.37	65.9	51.73	17.32	1.396
42	112- "	17.91	11.58	64.6	54.83	17.62	0.980
43	113- "	17.86	11.40	63.8	56.65	17.89	1.503
44	114- "	19.27	11.28	58.5	70.82	19.28	1.997
45	115-6.0200 W	41.77	11.73	28.2	256.11	38.54	1.919
46	116- "	39.84	11.65	29.2	241.86	38.35	2.154
47	117- "	35.41	11.72	33.2	202.25	35.08	2.026
48	118- "	32.64	11.51	35.2	183.64	31.72	1.888
49	119- "	38.00	11.72	30.9	221.33	36.34	1.735
50	120- "	32.23	11.60	36.0	177.93	30.80	1.759
51	121- "	33.20	11.65	35.1	185.12	32.17	1.860
52	122- "	31.56	11.71	37.2	169.47	30.76	1.933
53	124-4.0300 W	28.93	11.35	39.3	154.85	27.33	2.036
54	125- "	31.25	11.56	37.0	170.45	29.65	1.808
55	126- "	29.37	11.58	39.4	153.57	27.94	2.093
56	127- "	28.05	11.89	42.4	135.87	26.40	2.095
57	128-4.0703 W	17.54	11.43	65.2	53.46	17.32	1.250
58	129- "	17.79	11.43	64.4	55.70	17.82	1.266
59	130- "	15.66	11.21	71.6	39.67	15.52	0.847
60	131- "	17.30	11.21	64.8	54.34	17.31	1.088
61	132- "	17.78	11.36	63.9	56.52	17.72	1.230
62	133- "	17.90	11.30	63.1	58.47	17.87	1.589
63	134- "	17.52	11.33	64.7	54.63	17.47	1.480
64	135- "	15.45	11.20	72.5	37.88	15.49	0.655

APPENDIX I
THE TESTING PLANT

APPENDIX I

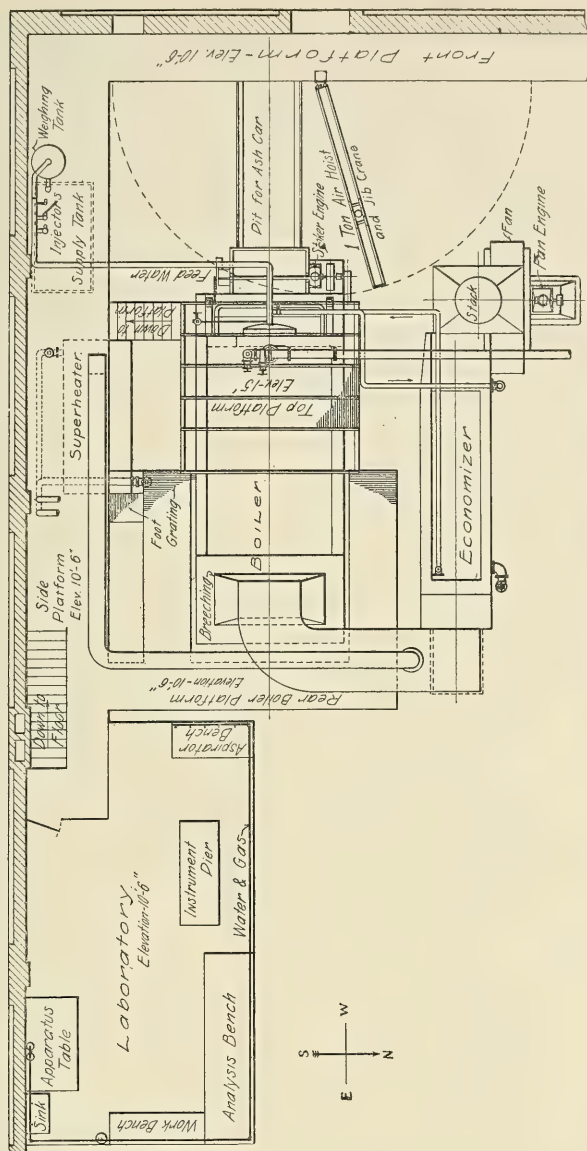
THE TESTING PLANT

81. *Equipment Used.*—The equipment especially provided for the steaming tests of fuels is located in the south bay of the Mechanical Engineering Laboratory. It includes a 210 horse-power Heine water-tube boiler, designed for a working pressure of 160 pounds, a Green traveling link grate and furnace, a Sturtevant induced draft apparatus and economizer,* and the usual small auxiliary apparatus. Additional equipment for use in experimental investigations includes the usual and special apparatus for weighing the coal and ash, for weighing and measuring feed water, for determining pressures, temperatures, and the quality of the steam, and for sampling and analyzing gases. Special apparatus for high temperature measurements which are available includes the Wanner optical pyrometer, Fery radiation pyrometer, thermo-electric, and platinum resistance thermometers.

82. *General Plan.*—The general plan of the testing plant is shown in Fig. 11. This arrangement was adopted with the object of facilitating experimentation, but was limited somewhat by the available floor area. The space occupied by the plant is 30 by 45 feet. The floor is of concrete, and all water supply pipes, drains, exhaust pipes from the auxiliary engines, and the blow-off pipes from the boiler, are laid in concrete trenches which connect at the rear of the plant with a 24-by 24-inch branch of the main laboratory pipe tunnel. The trenches are covered with cast-iron floor plates flush with the floor. The 24- by 24-inch trench, carrying the blow-off pipe and drains, leads through the south wall of the building and discharges into a creek running near by.

To provide easy access to the breeching and upper parts of the boiler, there is a deck surrounding the setting on three sides and extending to the south wall of the building at an elevation of $10\frac{1}{2}$ ft. This is constructed of iron channels supported by iron columns and wall brackets. The floors are of iron grating and plates. It extends along the west wall and joins the central gallery of the building, and along the south wall toward the rear of the boiler room opens into a 14 by 24 ft. laboratory at the same elevation, (Fig. 11 and Fig. 14.) At the front of the boiler, (Fig. 12,)

*Not used in the present experiments.



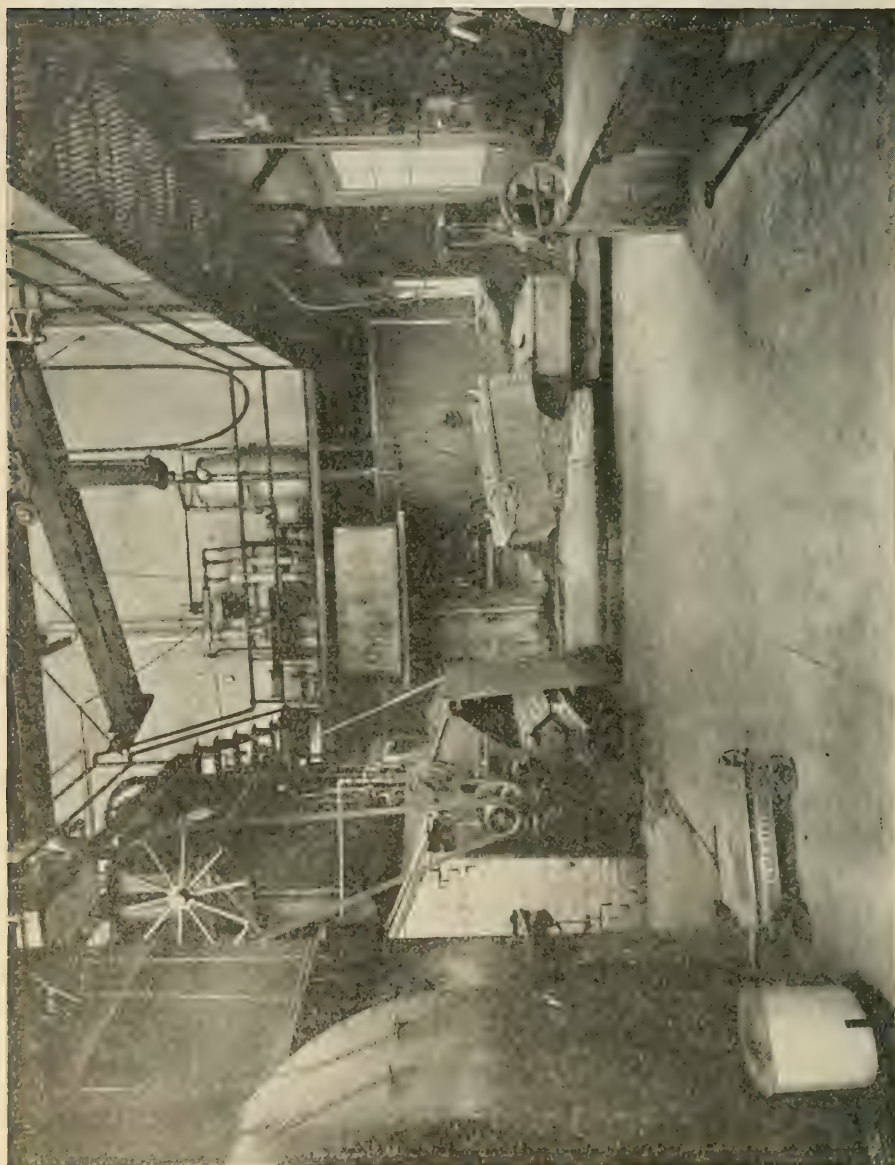


FIG 12. FRONT VIEW OF BOILER ROOM

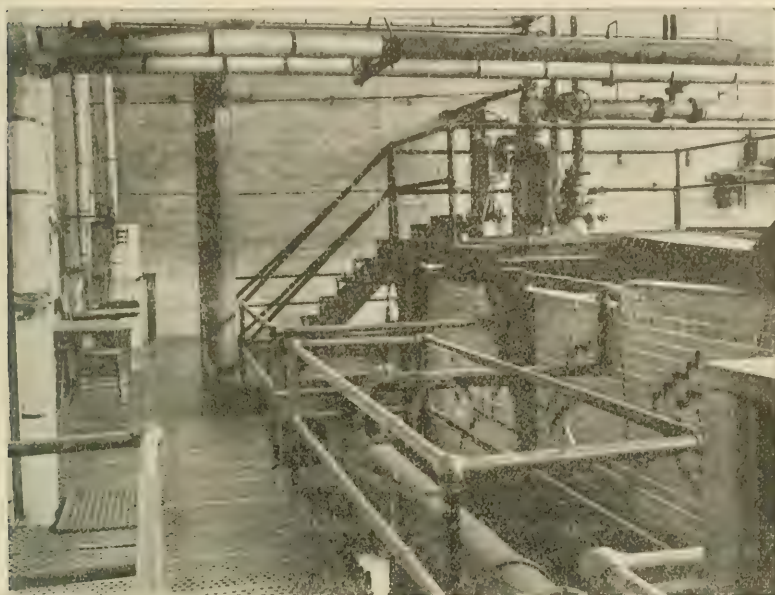


FIG. 13. ARRANGEMENT OF THE UPPER DECKS

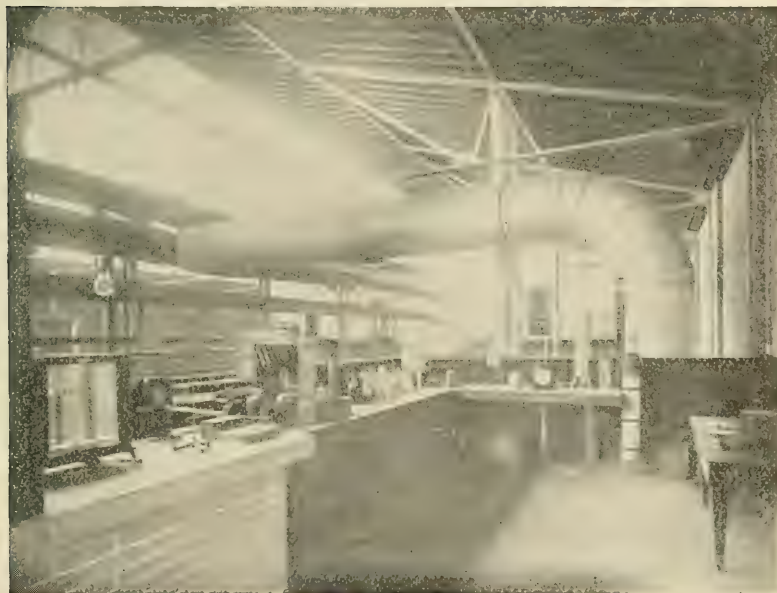


FIG. 14. LABORATORY FOR GAS ANALYSIS

a short stair leads to a platform grating surrounding the uptake and header, and on the main deck at the foot of these stairs are located the feed water weighing tank and injectors. The 14-by 24-ft. laboratory, Fig. 14, is used for all observations that can be made at a distance from the boiler. Here are located the aspirators for drawing gas samples, apparatus for gas analysis and the various kinds of indicating and recording apparatus for temperature measurements. A 3-by 7-ft. stone-capped instrument pier is provided to support galvanometers and delicate instruments.

Fig. 11 shows, also, the location of a Foster independently fired superheater which is a part of the general equipment of the Steam Engineering Laboratory.

82. *Boiler and Combustion Chamber.*—The Heine water-tube boiler installed in this plant is similar in every respect to the boilers which were in use for some two years at the fuel testing plant of the United States Geological Survey at the World's Fair Grounds, St. Louis, and with the exception of material used in the construction, the setting is the same and the boilers similarly baffled. The essential difference is in the furnaces, the Geological Survey's boilers being equipped with plain and with rocking grates.

A sectional elevation of the boiler is shown in Fig. 15 and the baffling and other features of the setting in Fig. 16. The walls of

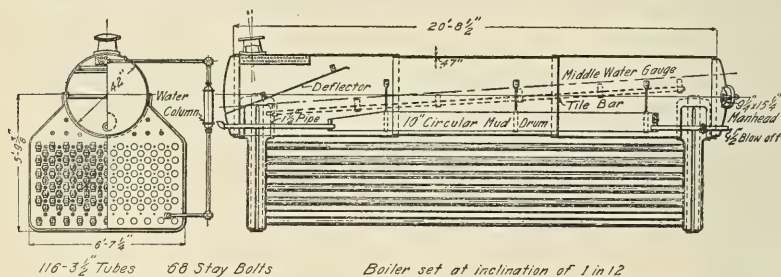


FIG. 15. DETAILS OF THE 210 H. P. HEINE BOILER

the setting are 20 in. thick with a 2-in. air space as shown. Hard face brick, closely laid, were used on the outside walls, and in the furnace, combustion chamber and gas passage, the fire brick lining extends to the top row of tubes. Regular Heine *C* tube tiles are used in the construction of the combustion chamber roof which extends to within 43 inches of the rear water leg.

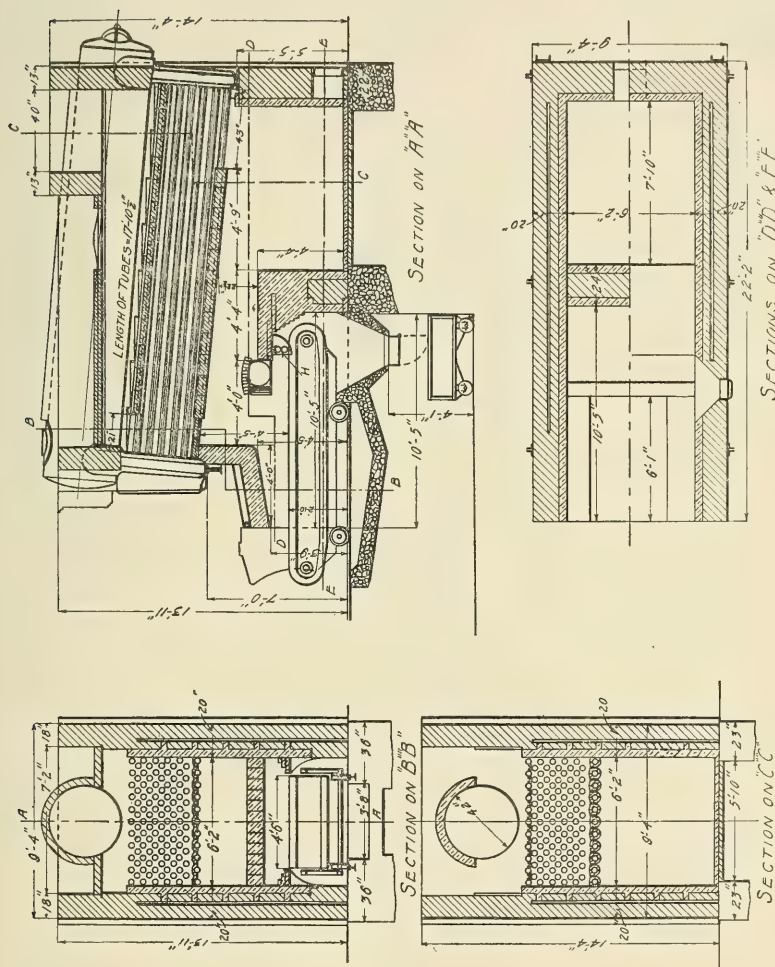


FIG. 16. DETAILS OF THE BOILER SETTING

83. *The Principal Dimensions of the Heine Boiler, and the traveling link grate and furnace are as follows:*

Rated horse-power.....	210.0
Number of steam drums	1
Length of steam drum.....feet.....	21.583
Inside diameter of drum.....inches.....	42
Number of tubes.....	116
Outside diameter of tubes	inches..... 3.5
Inside diameter of tubes.....	inches..... 3.26
Mean length of tubes exposed to gases.....feet....	17.875
Kind of grate.....	Green traveling link
Width of grate.....	inches..... 54
Effective length of grate.....	inches..... 102
Area of grate surface.....	sq. ft..... 38.2
Area of air space in grate.....	sq. ft..... 8.25
Ratio of air space to grate area.....	0.216
Mean height of furnace between ignition arch and bridge wall.....	inches..... 48
Length of ignition arch.....	inches..... 48
Mean height of ignition arch.....	inches..... 15
Kind of draft.....	Induced
Height of stack above grate.....	feet..... 45.5
Diameter of stack.....	inches..... 40.0
Sectional area of stack....	sq. in.....1250
Area of gas passage over the bridge wall..	sq. in.....1665
Smallest area of gas passage between grate and lower baffle.....	sq. in.....1665
Area of opening through lower baffle.....	sq. in. ....1677
Smallest area of gas passage between upper and lower baffle.....	sq. in.....1612
Area of opening through upper baffle.....	sq. in..... 746
Area of gas passage entering breeching ...	sq. in..... 625
Ratio of smallest gas passage to grate area.....	.113
Water heating surface in tubes.....	sq. ft.....1900
Water-heating surface in shell, legs, etc....	sq. ft..... 127.4
Total water-heating surface.....	sq. ft.....2027.4
Ratio of heating surface to grate surface.....	53.1
Total water space.....	cu. ft..... 273
Total steam space.....	cu. ft..... 85

84. *Grate and Furnace.*—The traveling link grate, Fig. 17, and furnace are the standard type supplied by the Green Engineering Company. Two features of this grate are the long flat ignition arch and the high bridge wall. The special ledge plates shown in the section *BB*, Fig. 16, are, however, a slight modification of the standard installation, being so designed that for experimentation, a change can be made to a hand-fired grate without changing the walls of the setting.

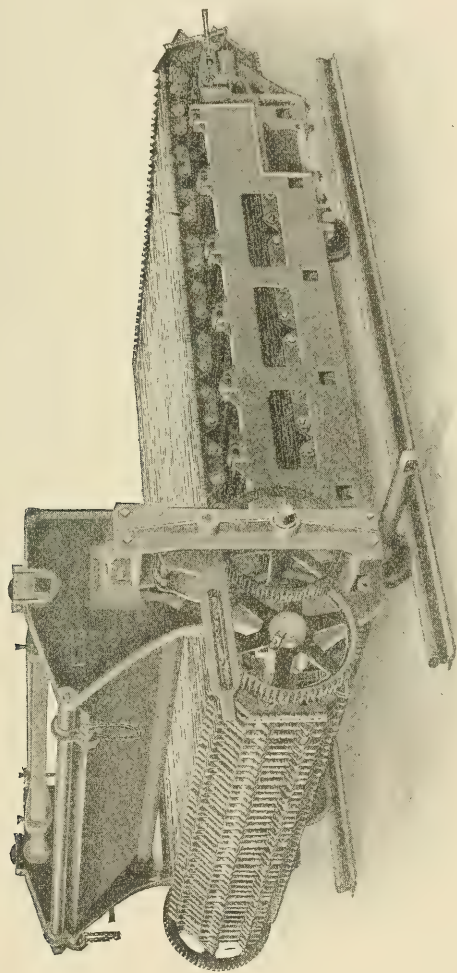


FIG. 17. THE GREEN TRAVELING LINK GRATE

85. *The Water-Back.*—The Harrington automatic water-back installed with this grate is indicated at *H* in Fig. 16. It consists of two connected iron cylinders extending across the width of the grate, supported by the furnace settings and so hung that the lower one rides upon the ash and clinker, and is free to move in a circular arc about the axis of the upper stationary cylinder. The free adjustability of the lower cylinder necessitates a flexible coupling to the water supply and for this reason the circulating water is supplied independently of the boiler.

86. *Ash Handling.*—Ash from the grate is removed by means of a car which runs along a track at the bottom of the ash tunnel to the front of the boiler, where it is handled by a one-ton air hoist and jib crane for removal to trucks, or, first, to scales for weighing as desired. The ashpit is provided with a concrete hopper fitted with a hinged door so that the ash may be retained in the hopper while the ash car is being emptied.

87. *Induced Draft.*—The plan and elevation of the induced draft system and economizer are shown in Fig. 18. By reference

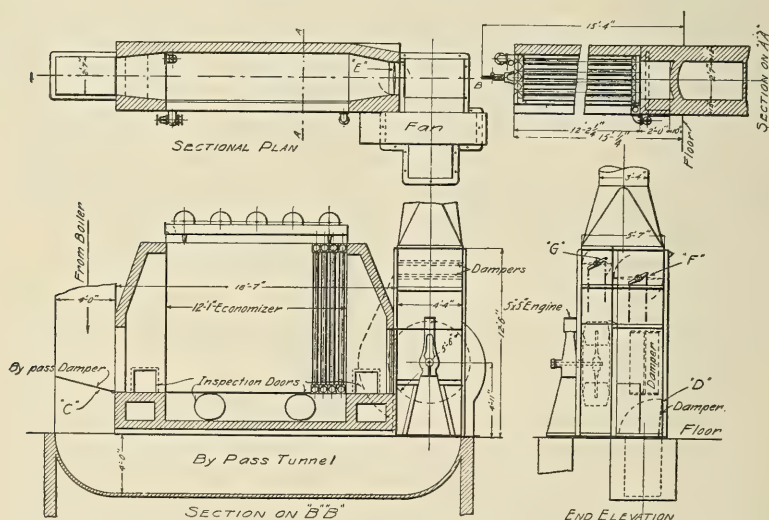


FIG. 18. SECTIONAL VIEWS OF THE INDUCED DRAFT SYSTEM AND THE ECONOMIZER.

to this it will be seen that there is a by-pass tunnel for the escaping gases so that when it is desired to cut out the economizer, damper *C* can be thrown to a vertical position, damper *E* set

at right angles to the center line of the economizer, and *D* raised to a vertical position. Provision is also made for direct chimney draft by leaving damper *G* as shown and setting *F* vertical, the draft pressure being controlled by an independent damper in the breeching or by the damper *F*. The height of the stack, however, is not sufficient for operation under chimney draft.

The fan is a regular Sturtevant steel plate exhaust fan with blast wheel $5\frac{1}{2}$ ft. in diameter and $22\frac{1}{2}$ in. in width, directly connected to a 5 by 5 upright enclosed engine mounted on a sub-base which stands directly against the fan housing. The inner bearings of the engine are water cooled. Since installation, this engine has been fitted with a Waters' throttling governor.

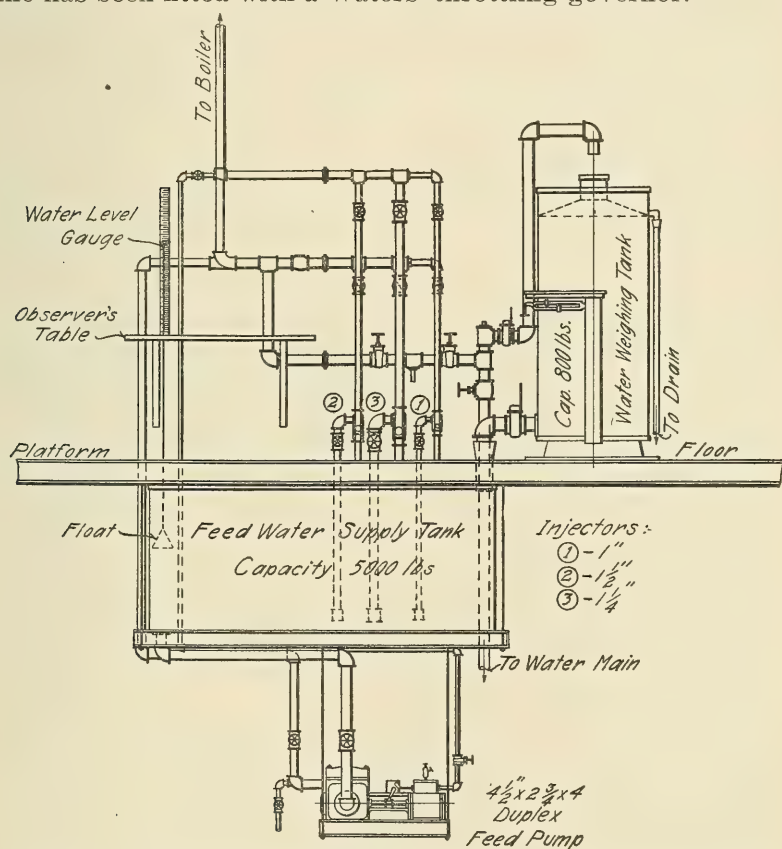


FIG. 19. SHOWING ARRANGEMENT OF WATER-WEIGHING APPARATUS, INJECTORS, PUMP, ETC.

88. *The Economizer.*—The economizer was not used in these tests, but to complete the description of the plant a description is given. This economizer, one of B. F. Sturtevant Company's standard design, consists of 80 pipes, 4 9-16 in. outside diameter and 9 ft. in length, giving a total heating surface of 1001 sq. ft., (4.77 sq. ft. per rated boiler horse-power independent of economizer), and a capacity of 5040 lb. of water. The pipes are arranged in twenty sections of four pipes each, and are staggered. The location of the economizer is shown in Fig. 11. The feed water connections are by-passed so that the economizer may be cut in or out at will. During the series of tests reported in this paper, the connections between the boiler and economizer were removed.

89. *Piping.*—For supplying feed water to the boiler there are provided both injectors and a $4\frac{1}{2}$ - by $2\frac{3}{4}$ - by 4-inch duplex steam pump; the latter is controlled by a Vigilant feed water regulator. All steam and feed lines are well lagged with magnesia covering, and all water by-pass valves are in duplicate, and the intervening dead space vented so that no undetected leakage can occur; flanged couplings are also used to provide for blanking off the by-pass lines when necessary. A similar arrangement of stop-off valves and vents is used for detecting leakage through the blow-off valves.

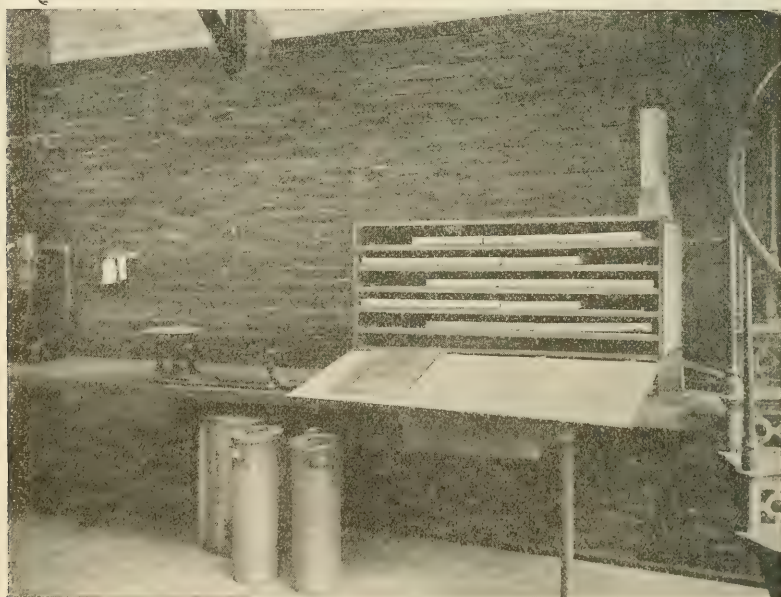


FIG. 20. OVEN FOR AIR-DRYING COAL SAMPLES

90. *Setting Wall Diagrams.*—The diagrammatic sketches, Fig. 21 and 22, which show opposite sides of the boiler setting, give the location of the points at which various routine and special observations have been taken. They are the permanent lab-

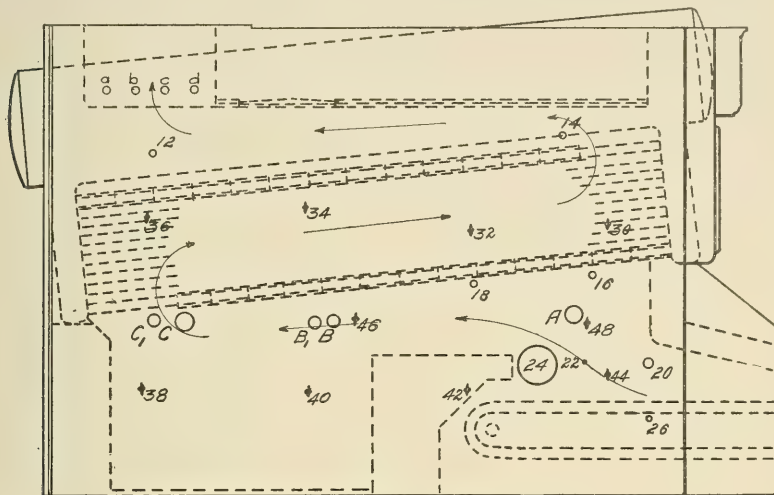


FIG. 21. NORTH SETTING WALL

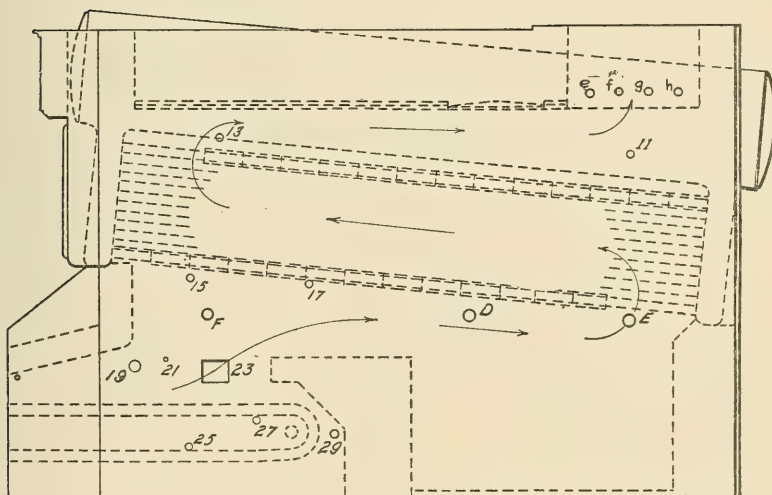


FIG. 22. SOUTH SETTING WALL

oratory record of such locations, consequently some openings appear in the diagram which have been subsequently closed.

The points 11 to 29, excluding 23 and 24, which are the furnace inspection doors, are openings used at various times for the measurement of draft pressure and temperature observations within the furnace or gas passage.

Openings *a*, *b*, *c*.....*h*, were used for special investigations relating to methods of gas sampling. See page 88. The points numbered in even numbers from 30 to 48 show the location of mercury thermometers imbedded in the surface of the wall; they are useful in keeping a check on the wall temperature.

The openings *A*, *B*, *B*₁, *C*, (Fig. 21), etc., are used for special furnace temperature measurements with various types of pyrometers and for observations relating to the extent of the flame within the combustion chamber. They consist of iron pipes extending through the walls and capped on the outer end. The interior is observed through smaller holes in the caps, and the holes closed by sliding shutters between observations.

APPENDIX II

EXPERIMENTS RELATING TO FLUE GAS DATA AND METHODS
OF MAKING AND RECORDING FURNACE OBSERVATIONS

APPENDIX II

SAMPLING FLUE GASES

91. It is common experience that samples of flue gas taken simultaneously at different points across any section of the gas stream flowing through a boiler, show different proportions of air and combustion gases. This condition is due to the fact that the air supplied to the furnace is never uniformly distributed, and does not become diffused in the passage through the boiler; also, unless the utmost care is observed, samples taken at the breeching or across the base of the stack may be further affected by leakage of air through the setting. The worst feature of the latter occurrence, even when the analysis is desired only for computation of heat loss, is that such excess air has even less chance to become diffused than that entering the furnace.

92. For the purpose of determining what the actual conditions were in this experimental plant, eight separate sampling pipes, perforated with $\frac{1}{16}$ in. holes along their full length were inserted at points *a*, *b*, *h*. See Fig. 21 and 22, page 85. The setting walls are of pressed brick and every precaution was taken to insure against leakage of air into the gas passages between the furnace and sampling tubes. The sampling tubes were connected by separate tubes to a large Richards aspirator. While the gas was thus being drawn at a uniform rate for all tubes, one-minute samples were simultaneously drawn from the tubes through connections. Four sets of samples were drawn in this manner on different days. Analyses of these are given in Table 25, which shows the percentage by volume of carbon dioxide in the gases.

TABLE 25 VARIATION IN FLUE GAS SAMPLES

Carbon Dioxide per cent	Trial	TUBES							
		a	b	c	d	e	f	g	h
	A	4.2	4.8	4.6	4.6	5.6	4.2	5.2	4.2
	B	4.8	5.4	5.1	....	7.1	7.1	7.1	4.5
	C	7.2	8.4	10.6	10.8	8.8	6.2	7.2	5.8
	D	7.5	8.0	9.6	10.4	10.2	9.6	8.8	7.3

93. The imperfect mixing of the gases and air as they come from the furnace is attributed to the fact that free air enters along

the sides and rear of the grate, and as there are no mixing baffles in the furnace and the boiler is baffled horizontally, the different streams are never wholly intermixed. The outside streams are consequently diluted. Tracing the course through the boiler of an imaginary layer of free air flowing into the furnace at the rear of the grate, will afford sufficient explanation for the difference in dilution shown.

94. As a result of the conditions disclosed by these results, it was decided to try some means of mixing the gases, the outcome of which is the device shown in Fig. 23. This arrangement con-

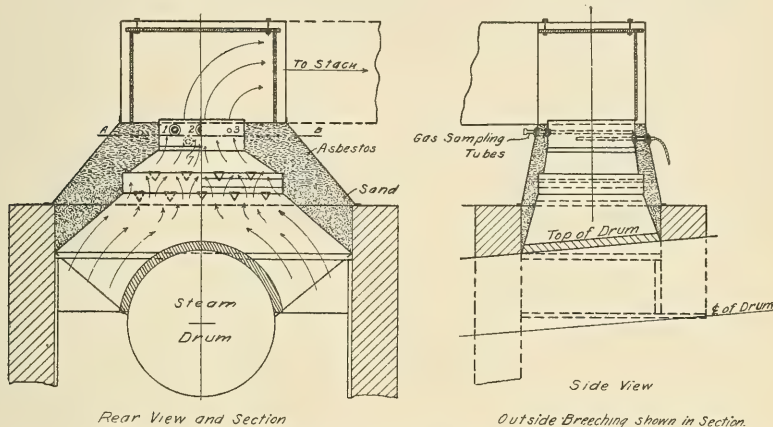


FIG. 23. SECTIONS OF BREACHING SHOWING FLUE GAS MIXING BAFFLES AND SAMPLING TUBES

sists of a well insulated false or inner breaching, within which the gases are compelled to pass through a series of mixing baffles and converge into an uptake constricted to 21 by 21 in., the latter forming a sampling section across which the gases are thus compelled to flow with nearly uniform velocity. To prevent leakage from the outer breaching into this inner breaching, all seams are effectually closed with iron cement, the filling of insulating sand acting as a further precaution.

95. Three gas sampling tubes 1, 2, and 3, Fig. 23, consisting of $\frac{3}{8}$ -in. pipe, capped on the inner end, and perforated with a double row of $\frac{1}{16}$ -in. holes spaced 3 in. apart along the under side, were equally spaced across the gas passage. These were brought together on the outside by means of $\frac{1}{4}$ -in. lead pipe uniting in a junction box, from which a single lead pipe conducted the gas sample to the gas apparatus and aspirator. By means of tees in

the leads to the junction box, simultaneous samples could be drawn from each of the separate tubes while the aspirator was in action drawing the regular test sample. A number of samples were taken in this manner during several tests, care being taken as in the previous experiments that the rate of sampling from each tube was equal. The results of analyses of these samples are given in Table 26 and 27. An inspection of the results shows that marked improvement in the sample was thus effected.

TABLE 26 COMPARISON OF GAS SAMPLES DRAWN FROM SEPARATE TUBES FIG. 23

No.	Per cent Carbon Dioxide				No.	Per cent Carbon Dioxide			
	Tube No. 1	Tube No. 2	Tube No. 3	Average		Tube No. 1	Tube No. 2	Tube No. 3	Average
1	7.6	7.2	6.9	7.2	18	11.7	11.7	11.4	11.6
2	7.5	7.0	6.8	7.1	19	10.7	10.0	8.5	9.7
3	7.5	7.1	6.8	7.1	20	9.8	8.9	8.0	8.9
4	11.1	10.9	10.6	10.9	21	9.9	9.9	8.8	9.5
5	9.8	9.5	9.4	9.6	22	11.2	10.0	9.0	10.1
6	4.5	4.7	4.9	4.7	23	10.1	9.7	9.0	9.6
7	3.9	3.7	3.7	3.8	24	11.4	11.5	11.2	11.4
8	6.8	6.1	6.0	6.3	25	11.0	11.1	11.0	11.0
9	6.7	6.5	5.8	6.3	26	9.2	9.2	9.2	9.2
10	6.7	6.1	5.9	6.2	27	8.5	8.6	8.3	8.5
11	6.2	6.0	5.8	6.0	28	11.1	10.5	10.5	10.7
12	8.2	7.1	6.6	7.3	29	12.6	11.1	10.7	11.5
13	12.8	11.1	10.8	11.6	30	13.6	13.9	13.8	13.8
14	12.5	11.2	10.8	11.5	31	9.9	10.0	9.8	9.9
15	11.9	11.3	10.5	11.2	32	12.3	10.8	10.5	11.2
16	13.9	13.8	13.4	13.7	33	10.2	9.2	9.0	9.5
17	12.1	11.6	10.9	11.5	34	9.6	9.6	9.3	9.5

TABLE 27 COMPARISON OF GAS SAMPLES DRAWN FROM SEPARATE TUBES FIG. 23

No.	Carbon Dioxide				Oxygen				Nitrogen			
	Tube No. 1	Tube No. 2	Tube No. 3	Av.	Tube No. 1	Tube No. 2	Tube No. 3	Av.	Tube No. 1	Tube No. 2	Tube No. 3	Av.
1	5.7	5.8	5.7	5.7	14.4	14.3	14.3	14.3	79.9	79.9	80.0	79.9
2	8.1	7.8	7.5	7.8	11.6	11.9	12.2	11.9	80.3	80.3	80.3	80.3
3	8.5	7.7	7.5	7.9	11.5	12.4	12.7	12.2	80.0	79.9	79.8	79.9
4	7.6	7.2	6.9	7.2	12.1	12.5	12.8	12.5	80.3	80.3	80.3	80.3
5	7.5	7.0	6.8	7.1	12.1	12.7	12.8	12.5	80.4	80.3	80.4	80.4
6	7.5	7.1	6.8	7.1	11.7	12.8	13.1	12.5	80.1	80.8	80.1	80.3
7	13.9	13.8	13.4	13.7	5.8	5.8	5.8	5.8	80.3	80.4	80.8	80.5
8	12.1	11.6	10.9	11.5	6.7	7.4	8.3	7.5	80.8	81.0	81.2	81.0
9	9.4	8.8	8.3	8.8	10.2	10.9	11.3	10.8	80.4	80.3	80.4	80.4

96. *Improved Form of Gas Sampling Tubes.* At the close of the present series of tests, an improved form of gas sampling tube designed by the writer was introduced. This consists of a pair of tubes intended to compensate for drop in pressure along the tube. See Fig. 24. The lower parts of the loops are per-

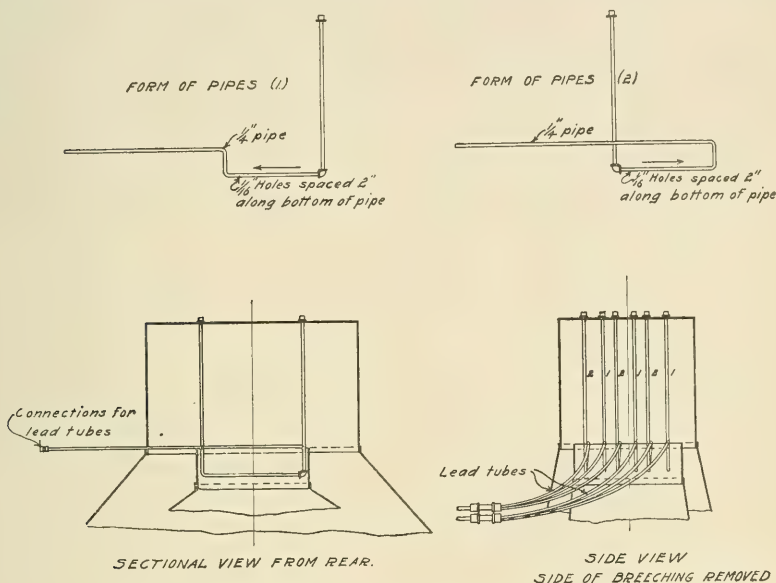


FIG. 24. IMPROVED FORM OF GAS SAMPLING TUBES

forated with single rows of $\frac{1}{16}$ -in. holes spaced two inches apart, the gas traveling in the direction of the arrows. The other sampling pipes were removed and three pairs of these tubes placed across the sampling box. The tubes drop into the sampling box from above so that perforation of the box is avoided and the possibility of leakage is further eliminated. At the outside, the pipes are brought together by means of $\frac{1}{8}$ -in. lead tubing, into a junction box from which a $\frac{1}{4}$ -in. lead tube conducts the gas to the apparatus bench and thence to the aspirator as before. The capped ends of the sampling tubes are bent upward and pass out through the breeching to facilitate cleaning. Just previous to the start of each test the tubes are cleaned with compressed

air, which is applied through the junction box, and the end caps are removed occasionally to permit blowing out dust which gradually accumulates at the bend near the last hole. Special tests of the new sampler have not been made so that it is not known whether any real advantage has resulted.

97. It should be remembered that this gas mixing device was designed to meet special conditions brought about by the course which the gases take in leaving this boiler and by the sharp angle in the breeching just above the boiler. It is possible that had the boiler been surmounted by a straight stack, other and more simple means could have been employed. The effect of the baffles on the draft is so considerable that it can be used only where high force of draft is available.

METHOD OF MAKING AND RECORDING FURNACE OBSERVATIONS

98. A careful record of the characteristics shown by the fuel bed is a necessity in the study and comparison of fuels. With the exception of the flue gas data, no other set of data is as generally useful in the analysis of variations which show up in the results. However, if such a record is to be of use, the relative value of various occurrences which affect the furnace and fuel performance must be clearly recognized and the notations which are made during the experiment, recorded in a systematic manner. Experience with the common methods of recording furnace observations and certain isolated test data in the form of running notes has shown the insufficiency of such methods for the purpose of a comparable record, not because such notes may not be made sufficiently full, but chiefly because of their lack of system both in arrangement and in the descriptive terminology used. To eliminate discordance from those sources in this series of tests and to provide for a general summary of the data, two convenient report forms were used.

99. See Form 1, p. 93; Form 2, 96-97. The description which follows will show the various purposes which these forms have served. Their presentation here is essential in that they will convey some idea of the effort made to secure consistent operation and comparable data.

100. *The Furnace Condition log* is a record of the various items included and affords a permanent record of variations in the operation of the grate and furnace.

101. *The Furnace Observer's Report*, which was always made out immediately upon the close of each test, takes care of the averages from the furnace log and a number of miscellaneous items, a permanent record of which is desirable. Further and of more importance, the report is intended to maintain a daily balance of the deductions reached, relative to the fuel, from the point of view of the furnace observer. An explanation of the various items is as follows:

THE FURNACE CONDITIONS LOG

"Condition of Fuel Bed at Rear of Grate"

In recording the degree of adherence to the conditions adopted for the control of the furnace and the fuel bed area, the following terms have been useful.

1. *"Banked"*—Live fuel against the water-back and thicker than at the center of the grate, live fuel also falling into the ash-pit.
2. *"Close"*—Live fuel against the water-back, but none passing to the ashpit.
3. *"Clear"*—Edge of fuel line completely burned out just at the water-back.
4. *"Inches of grate clear"*—Distance in inches, estimated, of the live fuel line from the water-back.

In using these terms the fuel was considered to be completely burned when both flame and incandescence had disappeared.

102. *Recording the Observations*—Observations relating to the area of the fuel bed were not made simply at the regular 15 minute periods. The three columns 2, 3 and 4, provide for a record of the maximum, minimum and average distances from the water-back, so that the record is really a continuous one. The average recorded is a weighted average, depending upon the judgment of the observer. It is not the mean of the maximum and minimum observations. A mica window in the inspection door allowed easy observation of the conditions within the furnace. The simple fact that continuous record is being kept of the maximum and minimum

area of the fuel bed has a salutary effect in preventing uncalled-for irregularities in the operation of the grate.

Change of Grate Speed—Column 5. In this column the number of adjustments found necessary to comply with the other requirements is recorded.

Average Area of Holes in the Fuel Bed—Column 6. Any entirely burned out spot in the fuel bed greater than six inches in diameter was considered a hole in the bed, and the average total area of these was recorded for each 15-minute period. The mean of column 6 was recorded on the Furnace Observer's Report, also the maximum and minimum area shown by the 15 minute readings.

A tabulation of the results of these observations, taken from the Furnace Observer's Report, will be found in Table 40.

Leveling the Fire—Columns 8 and 9 provide for recording the time of leveling. Leveling in the sense in which we have used the term does not have the significance for which it is used in a hand-fired furnace. That is, it does not signify that the whole fuel bed has been leveled. In these tests, whenever holes were leveled or fuel pushed to the sides of the grate, a, "leveling" was recorded. In the Furnace Observer's Report, in order to facilitate comparison, this item is based on a four-hour period.

Slicing—Column 10. Slicing the fuel bed in chain grate operation usually consists simply of running the slice bar along the ledge to remove any adhering clinker which might otherwise accumulate, to reduce the grate area or disturb the fuel bed along the sides.

A record of the number of slicings and the time at which they were made gives double assurance that trouble from this source has been avoided.

FURNACE OBSERVER'S REPORT

Items 1 to 8. These items are intended as a check on some of the principal items of the test. It was one of the duties of the furnace observer to assure himself of the accuracy of the recorded weight of fuel and to see that the general and special control conditions were carried out. Item 8 is intended to keep track of any change in the control conditions outlined for the test. This item often constitutes valuable data, especially when it is found that the fuel will not respond to the draft pressure assigned, and further keeps track of changes made upon verbal instruction which might be misunderstood.

File No. _____

Class _____ No. _____ Observer _____

Fuel Index No. _____ Firemen _____

Series Test No. _____

Date _____

FURNACE OBSERVER'S REPORT

-
-
1. Flues when last blown: time _____ A. M., _____ P. M., Date _____
 2. Boiler and mud-drum when last blown off; Time _____ A. M., _____ P. M.
 3. Time of starting test _____, time of closing test _____
 4. Total pounds test fuel fired since last test _____
 5. Total pounds test fuel fired during test _____
 6. Thickness of fuel bed, inches _____
 7. Av. difference of pressure above and below grate, in. of water _____
 8. Change in control conditions preceding or during test _____
-

Why _____

SUMMARY OF FURNACE OBSERVATIONS

1. Conditions during the hour preceding start of test: Load _____
Draft, in furnace _____, in breeching _____
2. Conditions of fuel bed at rear of grate, per cent of time: Banked _____,
close _____, _____, nches clear _____
3. Fuel bed sliced _____ time, leveled _____, times av. four hr. period.
4. Area of holes in fuel bed, sq. in. (average of column 6); _____
Max., for 15 min. period _____, Min. for 15 min. period _____
5. Grate speed, constant or variable? Av. speed sq. ft. per hour _____
6. Was load easily maintained? _____ Why? _____
7. Was maximum rate of combustion attained? _____
8. Estimated increase of capacity obtainable by forcing _____
9. Would lower draft increase the evaporation? _____
10. Considering previous tests on this fuel (Index No. _____) which condition if any necessitated: _____

(a) Least attention to fuel bed and grate_____

(b) Most attention to fuel bed and grate_____

11. The preceding tests in order of the most favorable conditions are,

_____Remarks_____

General Remarks

Note—A list of descriptive terms has been selected for use in describing the general characteristics of the fuel bed, flame, etc. These should be adhered to as closely as possible. See "Instructions to Furnace Observer."

1. General appearance of fuel bed_____
_____2. Character of the flame_____
_____3. Appearance of refuse, clinker, etc._____
_____4. Change of firemen during test—time, etc._____
_____5. Change of furnace observer on this fuel_____
_____Remarks_____

Date_____

Signed_____

Summary of Furnace Observations

Item 1—This item relates to the condition of the fuel bed and furnace at the start of the tests.

Items 2, 3, 4 and 5—See under “Furnace Conditions” log above.

Items 6, 7, 8 and 9—Deductions entered under these items call into play the judgment of the observer. They are useful mainly in outlining further work on the fuel, though an observer of some experience will usually make very close deductions.

Items 10 and 11—Sub-items (a) and (b) are filled out after each test. They are useful in formulating the deductions called for under Item 11. The entry under the latter item and under “Remarks” summarizes the conclusions of the observer as far as his personal observations go.

General Remarks

Item 1—The entries under this item are difficult to systematize. The fuel bed may be open and burning evenly, broken and burning in spots, light and bulky, or it may lie on the grate in a compact mass with level surface. There are as many different modifications of fuel beds as there are kinds and grades of fuel. The fuel bed should be fully described, as upon its characteristics depend the distribution of the air supply and consequently the rate of combustion and the temperature obtainable.

Item 2—The amount of flame present in the furnace depends upon the amount of the volatile matter in the fuel and the proportion of air supplied. Observation of the flame is of interest chiefly in relation to the production or non-production of smoke. In the experiments flame which did not persist beyond point B (see Fig. 21, page 85) was denoted as “short” flame; flame which persisted beyond B was designated as “medium long” while flame of any volume entering the tube space at C, Fig. 16, was designated “long” flame. Flame, it should be understood, is long only because there is not sufficient oxygen in thorough mixture with the volatile matter to cause rapid combustion.

Item 3—Clinkering seldom gives serious trouble in chain grate operation. This item, however, takes care of any unusual occurrences.

Items 4 and 5—These items are intended to put on record in a conspicuous place any changes in the personal factor entering into the operation of the furnace.

APPENDIX III
EXPERIMENTAL METHODS

APPENDIX III

I. EXPERIMENTAL METHODS

An effort was made so to arrange the testing plant and to provide such instruments and facilities that the requirements of a test could be carried out with essential accuracy. In this appendix will be found a detailed description of the routine method pursued in collecting the data. The details of boiler performance are liable to so many uncertainties not accounted for in the mere statement of the code of the American Society of Mechanical Engineers that it is believed a description of the methods may assist engineers and students who may wish to make use of the collected data to give proper weight thereto.

In the tabulation of results, Tables 28 to 40, p. 121, the mean of the test readings from the observed data is given as recorded on the logs for each test, essential corrections to agree with the calibration of instruments having been made. Where data known to have been affected by inaccuracies are retained in the tables, attention is directed thereto in the itemized descriptions.

Weighing the Fuel and Ash.—In firing the furnace during a test, it has been found most satisfactory to feed the coal into the hopper by hand, although a specially designed coal bucket was available. The coal was weighed in a steel charging car made with one side hinged, shown in the photograph, page 76. The dimensions of this car are $2\frac{1}{2}$ ft. by $4\frac{1}{2}$ ft. by $1\frac{1}{2}$ ft. deep, and its capacity was about 700 lb.

During the tests, 500 lb. of coal was weighed at a time, the coal feed hopper was kept continually heaped a little more than full, and after each 500 lb. charge had been shovelled into the hopper, the coal was allowed to feed until a straight edge drawn across the top would give a level just even with the top edges of the hopper. The interval of time elapsing was recorded as the time of firing the charge. Other readings coincident with the time of firing were height of water in the water gage and the level of the water in the feed water supply tank. The time of weighing ash and refuse was likewise coincident with a "time of firing," though at less frequent intervals.

Sampling the Coal.—Samples of coal and ash could not be taken care of at the chemical laboratory until the morning following a

test, consequently, to avoid unaccounted-for changes in moisture content, the preliminary reducing, crushing and air drying of all samples were made in the boiler room.

In collecting the coal sample, two half shovelfuls of coal were taken for each 500 lb. charged during a test. The samples taken at each charge were at once crushed to less than quarter-inch size in a laboratory jaw crusher, and collected in a closely covered vessel. At the close of the test, a complete sample, weighing between 100 and 150 lb. or about 1 to 2 per cent of the total weight of coal fired during the test, depending upon the size of the coal, was carefully mixed and quartered down to about five pounds. From this, one kilogram was weighed out into a shallow pan for the determination of the moisture loss upon air drying.

Coal too wet for reducing at once in the jaw crusher was first sampled down to 10 kilograms, and this weight was given a preliminary drying in large pans set upon the grating surmounting the boiler. The temperature there ranged from 90° to 100° Fahr., and the drying was usually allowed to proceed over night. A record was then made of the loss, and the entire sample was reduced in the jaw crusher and further mixed and quartered down, and the air drying was concluded upon a 1000 gram sample, the total air drying loss in such case being given by the formula:

$$\text{Moisture, per cent} = a + \frac{100-a}{100} b; \text{ where } a = \text{the per cent}$$

loss in the preliminary drying and b = the per cent loss on the final sample.

A No. 80 Troemner's solution scale was used for weighing samples. This scale is very accurate and its construction allows the use of sample pans of any necessary size, the small sample pans used being 10 by 18 by 1 in. in depth, and the large pans 18 by 18 by 1 in.

In the final air-drying these pans were set away in a special sheet-iron oven, Fig. 20, the shelves of which are staggered to allow free circulation of air, which is induced by a Bunsen flame in the flue at the top. Since the air used for drying was not heated, the drying thus, at room temperature, required from three to four days, during which time the samples were weighed each day until the loss for the day preceding was less than 5 grams in 1000, when the samples were at once bottled in "Lightning" fruit jars and delivered to the chemical laboratory for final reducing and analysis.

Sampling the "Ash and Refuse."—The "ash and refuse" was removed from the ashpit, generally three or four times during a test. The contents of the car, weighing usually from 100 to 300 pounds, were dumped upon a smooth concrete floor and the clinker crushed with an iron tamp until all pieces were reduced to about $1\frac{1}{2}$ in. in size. The entire bulk was then mixed by twice shifting the pile, each shovelful being poured upon the center of the new heap so that the larger and heavier particles would, if possible, be evenly distributed. This bulk was then quartered, opposite quarters rejected and the tamping, mixing and quartering repeated until about 20 lb. remained. The particles were then reduced to about $\frac{1}{2}$ in. or less. This portion was then further reduced to $\frac{1}{8}$ in. or less by means of the jaw crusher, thoroughly mixed and a weight equivalent to 5 per cent of the original bulk preserved. This procedure was repeated for each quantity of "ash and refuse," and at the close of the test the aliquot samples thus obtained were thoroughly intermingled and quartered down to about two pounds, which was at once bottled for delivery to the chemical laboratory.

Feed Water.—The arrangement of the feed water system is shown in Fig. 19. The weighing tank has a capacity of 800 pounds, and is of the form commonly used for accurate measurement. It is provided with a small neck and an overflow. The tank is fitted with a 2-in. Lunkenheimer "Handy" gate valve on the supply pipe and a 3-in. similar valve on the discharge. It can be filled and emptied in about two minutes.

The number of tanks of feed water supplied to the boiler was recorded in the usual manner, recording both the time and number of the tank, and a check of the counts was maintained by means of a Bristol recording water-level gage connected to the 5000-lb. capacity supply tank. The temperature of the feed water was taken in the weighing tank before discharging. With the exception of tests 25 and 31, for which the pump was used, the boiler was fed by injector throughout the series. Three injectors, sizes 1, $1\frac{1}{4}$ and $1\frac{1}{2}$ in. were supplied so that a fairly steady feed was obtained for any rate of evaporation demanded from the boiler. The overflow from the injectors was returned to the supply tank, but since the temperature of the feed water was taken in the weighing tank, no correction for the weight or heat content of this overflow was necessary.

The total weight of water fed to the boiler, column 4, Table

32, is the weight of feed water by tank corrected for the following items:

1. Difference between the quantity of water weighed out and the quantity fed to the boiler; shown by the difference of the level of water in the supply tank at the start and close of the test.

2. Weight of feed water equivalent to the difference between the level of the water in the boiler at the start and close, with correction for the heat contained.

3. Water equivalent to the difference in the total heat of the boiler's water content at the start and close, due to difference between the steam pressures at those events.

4. Correction for leakage at the blow-off; pump leak, etc.

The total feed water weighed and the total correction applied, together with the data upon which this correction is based, are given in the water log, Table 31. The methods of arriving at the separate corrections follow:

1. Correction for level in supply tank: The supply tank was fitted with a delicate float gage which indicated the difference in level on a scale above. Each inch scale reading represented 145.5 lb. at 60° Fahr.

2. Correction for difference of water level in the boiler: It was endeavored to keep the water level within 3 to 6 inches, as shown on the water gage, middle gage being at 4.5 inches, and this was generally accomplished throughout the tests.

To allow correction for any differences of level at start and close, the boiler was carefully calibrated to each half inch on the glass. By this calibration, the water capacity of the boiler to middle gage is 17022 lb., and the average water capacity for each inch shown on the gage from 2½ to 6½ in. is 358.6 lb. at 62° Fahr. At 365° Fahr., corresponding to 150 lb. gage pressure, and further corrected for expansion of the boiler, one inch of water on the water gage represents 318 lb. average. This value was made the base for compensation for the thermal content of the weight represented by the difference in level in inches.

With more water in the boiler at the close than at the start, credit must be given for the heat required to raise the difference in weight from feed water to steam temperature. With the conditions reversed, credit must be given for evaporating the difference but not with heating it to steam temperature.

The correction to be applied to the feed water for each inch difference in level in the gage is given by the formula,

$$318 \times \left\{ 1 - \frac{q - q_1}{q - q_1 + \left(\frac{100-x}{100}\right) r} \right\}$$

where q = the heat of the liquid at steam temperature, q_1 = the heat of the liquid at feed water temperature, r = the heat of vaporization, and x = the per cent of moisture in the steam. The latter may be neglected in the calculations.

The corrections per inch of gage reading used in the test calculations were obtained from a chart based upon the above formula.

It will be seen that since the feed water temperature was from 55° to 60° Fahr. and the pressure from 145 to 155 pounds gage, the correction applied to the total weight of water fed was about constant at 233 lb. per inch of water gage difference.

3. Feed water correction for difference in steam pressure at start and close: This correction is a minor one, amounting to but 5.8 lb. of feed water to be added or subtracted per pound difference in steam pressure within the range of the experiments.

4. Correction for leakage at the blow-off valves: The lower blow-off valve began leaking during test No. 20 and continued until test No. 27, before repairs could be made. The leakage was conducted into a weighed tank of cold water and the weight of feed water to be subtracted in correction calculated by the formula:

$$\text{Correction} = (\text{Wt. of leakage}) \times \left\{ 1 - \frac{q - q_1}{q - q_1 + r} \right\}$$

The symbols have the usual significance. Peabody's steam tables were used throughout for the thermal properties.

Character of the Feed Water.—The water used in the test boiler and in the central heating plant comes from 125-ft. wells on the University grounds. The water is characterized by the presence of free sodium carbonate in amount greater than is necessary to satisfy any sulphates present, and consequently is absolutely non-scale forming.

Water of this character is found at a depth varying from 125 to 165 feet throughout an area of about 4000 sq. miles centering

about the University. It is also found in several other sections in Illinois at depths varying from 400 to 850 ft. A description of this water has been given recently by Professor S. W. Parr.* The normal amount of free alkali is about 5 grains per gallon.

During the progress of the tests, the writer personally inspected the boiler tubes on four occasions but no scale whatever was found. At the close of the series the tubes were as clean as when the boiler was first fired, save for the light coating of sludge dust which could be brushed away with the finger.

The Water-Back.—To avoid unnecessarily complicating the feed water system, the cooling water for the water-back was wasted to the drain. A measure of this water was kept by means of a carefully calibrated Breslau water meter placed in the inlet pipe, and to insure approximately a steady rate of flow through the meter, the temperature of the outflow was normally adjusted to a temperature from 80 to 100° Fahr., so that some variation in the range of temperature was allowable without complicating the measurements by too frequent adjustments.

Temperatures of the inflow and outflow and the meter's reading were taken at the regular intervals, and the amount of heat carried away by the cooling water was computed by taking the product of the total weight of water used during the test, corrected to agree with the calibration of the meter, and the average difference in temperature. The fact that an average was used here in place of the true mean introduces but a negligible error since the per cent loss of heat is in itself a relatively small item.

It may be said that the water-back can not be considered as being under practical test, but if one wishes to compute the amount of cooling water that would be required for various temperatures of the outflow, it may readily be done from the data given in Table 30.

The use of the adjustable water-back in the experimental plant has given the advantage of uniform conditions for fuels of varying character and ash content. No assumption is made, however, as to whether or not the adjustable water-back results in an economy over other methods of controlling the air leakage.

Compensated Water Items.—It will be noted that the tabulated water items and dependent items are expressed in two ways. Un-

* "Some Notes on the Service Waters of a Railway System," Jour. of the American Chemical Society, Vol. XXVIII, 5, 640, May, 1906.

der the regular A. S. M. E. code numbers are given the values obtained by actual performance, (designated "performance" in the headings). In adjacent columns and designated by the same code numbers, but with a decimal suffix, these items are raised to values which, it must be assumed, would have resulted had the water-back been of a stationary type in which the circulation water is taken from and returned to the boiler. These items are designated in the table headings "compensated for water-back" in brief for "compensated for the heat lost on account of the water-back". They are introduced for the purpose of eliminating variations. In making the compensations, the percentage loss of heat in the cooling water to the total heat of the fuel consumed has been added directly to the "boiler and furnace" efficiency per cent numbers, and the related water items and the numbers for

Item 73 raised by the factor $\frac{\text{Item 72} + \text{Heat loss per cent.}}{\text{Item 72}}$

Details of the calculations for different items are shown on pages 109 to 120.

Care of the Boiler.—Soot and dust are removed from the heating surface of the Heine boiler by means of a steam or air nozzle inserted through hollow stay bolts in the front and rear water legs. The nozzle used consists of a long pipe perforated at the end by a number of radial holes.

The surfaces were carefully cleaned, preceding each test, with an air blast of from 70 to 100 lb. pressure, blowing through each stay bolt in both front and rear legs and inserting the pipe the full length of the tubes. Several inspections of the tube surfaces showed that this treatment given each day maintained a remarkably clean surface, and since the furnace operated with but occasional traces of smoke, opportunity for coatings of tenacious character to form was entirely absent.

Starting and Stopping the Tests.—Running start and stop was necessarily made. With the chain grate the amount of ash upon the grate is practically constant, the depth of fuel entering the furnace is fixed by the gate opening and is not disturbed by motion of the grate. These circumstances are favorable to a running start yet the possibility of serious error is not obviated. Variation in weight of fuel upon the chain grate at start and close of the test may occur from one or all of several causes occurring or operating for a period required to displace the grate one effective

grate length just preceding either event. These are:

1. Difference in actual length of fuel bed.
2. Irregularity in speed of grate travel.
3. Variations in air supply.
4. Difference in the relative amounts of fine-sized fuel falling through the grate.

5. Differences occasioned by irregular attention to condition of the fuel bed.

6. Difference in clinkering or caking.

It is found that to bring the fuel bed to the same length just at the time of starting and stopping is not sufficient for accuracy. If it is necessary to quickly close up a short fuel bed to bring this about, the conditions are bad. One linear foot of grate travel carries into the furnace from 70 to 150 lb. of coal, depending upon the width of grate and depth of gate opening. Sudden changes of grate speed, consequently, produce excess or deficiency from the normal amount of fuel which should be upon the grate. Ideal conditions demand uniform rate of combustion and fuel bed length during the periods of time that determine the weight of fuel that will be upon the grate.

Variations due to these factors were avoided as far as possible by operating the grate under assigned test conditions for a period of from 30 minutes to 1 hour just preceding the start. The principal conditions observed were regularity of grate travel, and area of fuel bed and a constant "normal" draft pressure (see definitions, page 12).

For those tests in which the fuel clinkered more or less seriously, it was of course impossible to assure a uniform rate of combustion, and satisfactory agreement between starting and stopping conditions was more difficult to obtain. This difficulty was experienced with the fuel 5.1006 W. Satisfactory agreement was also difficult to obtain with the fine-sized coals. For several of the tests of fine sizes the furnace was operated under test conditions from 3 to 4 hours before acceptable conditions for starting were obtained.

Preceding all tests, the fireman operated the furnace as nearly as possible under assigned test conditions for two hours before the arrival of the regular observers, a check on the regulation during this period being maintained by means of recording gages for draft pressure and for temperature of the flue gases.

As an additional check on the starting conditions for all tests following test No. 27, the regular water readings were taken for 1 hour preceding the start and the load computed. If proper conditions of the furnace or load were not reached, the preliminary run was continued, taking readings as in the test proper. After one or two tests on each grade of coal, satisfactory starting conditions were usually obtained without trouble. The grate once adjusted to the requirements of the fuel and draft, closing conditions were usually readily obtained.

The fire was started each morning at 5 o'clock from a heavy banked fire, and was under full fire from $1\frac{1}{2}$ to 3 hours preceding all tests. The fuel to be tested was used during this period in order that the furnace and setting wall would be heated only to the normal temperature for that fuel; except in a few tests of the No. 5 coal, screenings were used for the first hour to bring the furnace to temperature more quickly. A check on the temperature of the furnace walls was obtained by means of thermometers slightly imbedded in the surface. The indications of these thermometers at all times varied more from drafts of air through the boiler room than from any difference of temperature within the furnace.

II. OBSERVED AND CALCULATED RESULTS OF TESTS

In the calculation of the results given in the tables following, the methods set forth in the code for boiler testing of the American Society of Mechanical Engineers, wherever they apply, have been followed in detail. Those items are tabulated under the regular code item numbers, and have the usual significance. Additional items are indicated by letters or by decimal suffixes to the usual code numbers.

In order to collect the results into compact and convenient tables and to provide space for additional items, it has been necessary in some cases to arrange the items in a different order from that usually followed in the A. S. M. E. code. For example, the items under the sub-head "water per hour" follow directly after "fuel per hour" in Table 33; the average steam pressure will be found under the heading "steam" in Table 30; draft pressures and air temperatures will be found under the headings "air" in Table 36; and the analysis of the flue gases and the per cent of smoke observed will be found in the same table. Other items

which are displaced from the arrangement of the A. S. M. E. code are "size of coal" and "thickness of fuel bed" Table 28; "temperature of the feed water" Table 32; "analysis of ash and refuse" Table 29; and "calorific value of the fuel" Table 39. In the following summary, the items are taken up in the order in which they appear in the tables.

TABLE 28. Principal Conditions—In this table those conditions which have the greatest effect upon the results of the tests are given. The items of Table 40 should also be consulted in a comparison of test results.

Column 1. Test number for this series.

Column 2. Laboratory file number. This number appears in each of the tables in the report and should serve as a convenient cross index to the fuel tested. The first part of the number refers to the files of the laboratory. All boiler or fuel tests made at the Engineering Experiment Station are given a general number and filed in that order regardless of the test series. General numbers not included are tests in other series, central heating plant tests or tests with house-heating boilers. The second part of the number is the fuel symbol, an explanation of which will be found on page 4.

Item 2. Duration of trial. The total time reduced to decimal number.

Commercial boiler trials are usually run for a ten hour period, the idea being that within that period sufficient total weight of fuel will be fired to minimize a reasonable and unavoidable error in judging the conditions and weight of fuel upon the grate at the start and close. In the adoption of a shorter trial period for this series, it is not intended to advocate any change in existing practice. Satisfactory starting and closing conditions with the chain grate, since they must be running conditions, are often and especially with non-uniform coal, much more difficult to obtain than for the plain grate using the "alternate method" of the American Society of Mechanical Engineers.

In these tests the duration of the trial has been wholly determined by the conditions under which the start and stop could be made, conditions which were in most cases favored by the superior and uniform grades of coal tested. It was usually endeavored

to prolong the trial until 200 lb. of coal had been fired per square foot of grate surface. This, however, was not always accomplished; a trial was to be run each day, the time of several men had to be regulated, and time allowed for the care of the boiler and the operation of the furnace under suitable conditions preliminary to the start.

The majority of the tests of short duration or in which less than a total of 200 lb. of coal was burned per square foot of grate surface, are duplicated on the same lot of coal. A comparison of the conditions and results for these duplicates is of interest. Short duration in tests 15, 44 and 64 was due to lack of sufficient supply of test coal for a longer period; however, the tests were run under favorable conditions. The conditions of test 15 duplicate those of test 14. The conditions under which tests 44 and 64 were made are not exactly duplicated by other tests. Test 8 was closed suddenly because of the blowing out of a gasket in the rear water leg. The close of the test was accepted as the time of the last coincident coal, ash and water reading; comparisons show the results to be good.

Item 23, Column 5. Size of coal.

Item 23, Column 6. Condition of coal.

Item 81, Thickness of fuel bed, inches. This is taken as the depth of the gate opening. The average thickness of the fuel bed upon the chain grate is, of course, less than this, but on account of the progressive combustion, this average can not be judged. However, a knowledge of the average would be of no more practical value than a record of the gate opening which can always be duplicated.

Item 13.1. Draft pressure in the furnace (assigned). This is the normal draft pressure assigned for the test. The averages of observed draft pressures are given in Table 30.

Column 9. Furnace control.

Column 10. Total coal fired per sq. ft. of grate area, pounds =
Item 25 ÷ 38.2.

TABLE 29. Coal and Ash—This table contains all items necessary for the calculation of the combustible consumed except the per cent of ash in the dry coal, Item 42, Table 38.

Item 25. Total weight of coal fired, pounds.

Item 26. Percentage of moisture in the coal as fired, pounds. See Item 34, Table 37.

Item 27. Total weight of dry coal fired, pounds = Item 25 $\times$ (1 - Item 26).

The term "fired" for obvious reasons is introduced here in place of the term "consumed" as used in the A. S. M. E. code. The term "consumed" is used in this report only in connection with that portion of the fuel or combustible which has been delivered beyond the bridge wall in the form of gases or carbon, i. e., the fuel or combustible fired minus that portion accounted for in the "ash and refuse".

Item 28. Total weight of dry ash and refuse, pounds.

Item 30. Total weight of combustible consumed. This is equal to the total weight of combustible (ash free dry coal) fired minus the weight of carbon in the "ash and refuse" = Item 27 $\times$ (1 - Item 42) - (Item 28 $\times$ Item 44).

Item 31. Per cent of "ash and refuse" referred to dry coal = Item 28 $\div$ Item 27.

Item 44. Per cent of carbon in dry "ash and refuse." By chemical analysis.

Item 45. Per cent of earthy matter in dry "ash and refuse". By chemical analysis.

Item 30.1. Total weight of dry coal minus the total weight of "ash and refuse", pounds = Item 27 - Item 38.

This item is given as a rough check on Item 30. Item 30.1 will generally be greater than Item 30 by a weight equal to the weight of ash carried beyond the bridge wall or collected on the walls of the furnace, though with well-sized clean coal the difference is usually small. Where Item 30.1 is the greater, it is usually due to increase in Item 28 from melting of the slag and fine ash which has accumulated on the face of the furnace walls and bridge wall during preceding operations. No error is introduced in Item 30 because of these gains or losses of ash, since the calculation is based upon the chemical analysis of the ash and refuse. Also any coal particles carried beyond the bridge wall settle in the combustion chamber and are completely burned in this furnace

TABLE 30. Steam and the Water-Back—This table contains all of the steam and water-back data and factors.

Steam:—

Column 3. Barometric pressure in lb. per sq. in.

Item 11. Average steam pressure by gage. The test boiler discharged its steam directly into a branch main of the central heating and power station, the normal pressure of which ranged between 130 and 145 pounds. The test boiler pressure was maintained at approximately 150 lb. gage by regulating the main steam valve. This was attended to by the water observer. An extra steam gage located below the valve and in view from the lower deck facilitated the regulation.

The steam pressures tabulated are the averages from Bristol recording gage charts. The steam pressures recorded at start and close, Table 31, are the indications of a standard gage of the Bourdon type. Both the recording and the standard gage were mounted on the same gage board and the two were compared at the start and close of each test. Both instruments were frequently checked by calibration.

Item 11.1. Absolute steam pressure = Item 11 + Column 3.

Item 54. Percentage of moisture in the steam. During the earlier portion of the tests, the moisture carried by the steam was determined by means of a Carpenter separating calorimeter. The six-inch vertical steam riser was well lagged; the sampling nipple was of standard design and located about 3 ft. above the boiler. At 4½ ft. above the boiler the riser ends in an ell connecting a special main 20 ft. in length. This short main connects with the branch main of the central heating plant by a down connection 10 ft. in length. However, to insure further that no condensation from the 20 ft. horizontal could return to the boiler, it was given a positive slope of 1 in. in 10 ft. The velocity of the steam in the riser is about 35 ft. per second when the boiler is delivering 210 H. P. The steam from the separating calorimeter was condensed in a special small worm condenser, the accuracy of the weight delivered by the orifice in no case being accepted.

This calorimeter was used up to test No. 24 when two other calorimeters were added for the purpose of checking. One of these was a throttling calorimeter of standard design; the other a very large special separating calorimeter so constructed that the orifice could be changed to different sizes as desired. It was found

that the throttling calorimeter gave approximately constant moisture readings. A series of experiments carried out at the same time by means of the large separating calorimeter, in which the total sample of steam drawn was gradually increased until the radiation from the well lagged calorimeter became negligible, confirmed the indications of the throttling calorimeter so that in the tests following test No. 23 the indications given by the throttling calorimeter were accepted.

It was found that a line drawn through all of the percentages thus obtained, the variation being from 0.5 to 0.7 of one per cent, was a constant at about 0.57. Since the radiation correction for the throttling calorimeter varies between 0.1 and 0.3 of one per cent it was concluded that the moisture content of the steam was constant at about 0.57 per cent, and this value was used in all tests following test No. 31, with the exception of tests 40, 41 and 42 where the variations were slightly in excess of the usual variation, as was the case likewise in the tests 24 to 30.

Item 56. Factor for correction for quality of steam =

$$1 - \left\{ \frac{\text{Item 54}}{100} \times \frac{q - q_1}{r + q - q_1} \right\} \quad \text{where } q = \text{the heat}$$

of the liquid at the steam temperature, q_1 = the heat of the liquid at feed water temperature, and r = the heat of evaporation at steam pressure. Values for q , q_1 and r were taken from Peabody's steam tables and a curve constructed from which the factors were taken for the computations.

The Water-Back. See page 82.

Item a. Total weight of cooling water used.

Item b. Temperature of inflow, average, degrees Fahrenheit.

Item c. Temperature of outflow, average, degrees Fahrenheit.

Item d. Ratio of the heat lost to the water-back to the total heat of the fuel consumed = Item a (Item c—Item b) ÷ (Item 30 × Item 51).

Item e. Water equivalent correction factor for the heat lost to the water-back = Item 72.1 ÷ Item 72. See page 106.

TABLE 31. Water Log Data—An explanation of this table together with the means of obtaining the weight of feed water, also the necessary corrections applied, are given on page 102.

TABLE 32. Total Water—All of the total water items are contained in this table.

Item 20. Temperature of feed water entering the boiler, degrees F.
See above.

Item 57. Total weight of water fed to the boiler, pounds.
See above.

Item 58. Equivalent water fed to the boiler from and at 212° F., pounds = Item 57 × Item 60.

Item 59. Water actually evaporated corrected for quality of steam, pounds = Item 57 × Item 56.

Item 60. Factor of evaporation = $(q - q_1 + r) \div 965.8$.

The thermal quantities were taken from Peabody's steam tables.

Item 61. Equivalent water evaporated into dry steam from and at 212° F., (performance) pounds = Item 59 × Item 60.

Item 61.1. Equivalent water evaporated into dry steam from and at 212° F., compensated for water-back loss, pounds = Item e × Item 61.

Item f. Total loss of equivalent evaporation charged against the water-back = Item 61.1 — Item 61.

TABLE 33. Fuel and Water per Hour—All fuel and water items calculated to the basis of one hour are collected under this head.

Fuel per Hour:

Item 46. Dry fuel fired per hour, pounds, = Item 27 ÷ Item 2.

Item 47. Combustible consumed per hour, pounds, = Item 30 ÷ Item 2.

Item 48. Dry coal fired per square foot of grate surface per hour, pounds = Item 46 ÷ 38.2.

Item 49. Combustible consumed per hour per square foot of water heating surface, pounds, = Item 47 ÷ 2027.

Water per Hour:

Item 62. Water evaporated per hour, corrected for quality of steam, pounds, = Item 59 ÷ Item 2.

Item 63. Equivalent evaporation per hour from and at 212° F. pounds, = Item 61 ÷ Item 2.

Item 64. Equivalent evaporation per hour from and at 212° F. per square foot of water heating surface, pounds, = Item 63 ÷ 2027.

Item 63.1. Equivalent evaporation per hour from and at 212° F. compensated for the water-back loss, pounds, = Item 63 × Item e.

Item 64.1. Equivalent evaporation per hour from and at 212° F. per square foot of water-heating surface, compensated for the water-back loss, pounds = Item 64 × Item e.

TABLE 34. *Horse-power and Economic Results*

Item 65. Horse-power developed = Item 63 ÷ 34.5.

Item 67. Percentage of builders' rated horse-power developed, per cent, = Item 65 ÷ 210.

Items 65 and 67 compensated for the water-back loss are given in Table 5 to 14.

Economic Results by Actual Performance:

Item 68. Water apparently evaporated under actual conditions per pound of coal as fired, pounds, = Item 57 ÷ Item 25.

Item 69. Equivalent evaporation from and at 212° per pound of coal as fired, pounds, = Item 61 ÷ Item 25.

Item 70. Equivalent evaporation from and at 212° per pound of dry coal fired, pounds, = Item 61 ÷ Item 67.

Item 71. Equivalent evaporation from and at 212° per pound of combustible consumed, pounds, = Item 61 ÷ Item 30.

Economic Results Compensated for Water-Back Loss:

Item 68.1. Water apparently evaporated per pound of coal as fired, pounds = Item 68 × Item e.

Item 69.1. Equivalent evaporation from and at 212° per pound of coal as fired, pounds = Item 69 × Item e.

Item 70.1. Equivalent evaporation from and at 212° per pound of dry coal fired, pounds = Item 70 × Item e.

Item 71.1. Equivalent evaporation from and at 212° F. per pound of combustible consumed, pounds = Item 71 × Item e.

TABLE 35. *Efficiency and cost of Evaporation—*

Item 72. Efficiency of the "Boiler and Furnace" = (Item 71 × 965.8) ÷ Item 51.

Item 73. The over-all efficiency = (Item 70 × 965.8) ÷ Item 50.

Item 72.1. Efficiency of the "Boiler and Furnace", compensated for water-back loss = Item 72 + Item d. See Table 30 for Item d.

Item 73.1. Over-all efficiency, compensated for water-back loss =
Item 73 $\times$ Item e.

Cost of Evaporation:

Item 74. Cost of coal per ton of 2000 lb. delivered in boiler room.
 This is arbitrarily taken as one dollar.

Item 75. Cost of coal for evaporating 1000 lbs. of water under
observed conditions, dollars, = $0.5 \div$ Item 68.1.

Item 76. Cost of coal used for evaporating 1000 lb. of water from
and at 212 degrees, dollars, = $0.5 \div$ Item 69.1.

TABLE 36. Air and Flue Gases. This table contains the items relating to the air supply and flue gases including the smoke observations.

Item 12. Average draft pressure between damper and boiler, in. of water. This was taken by means of an Ellison differential draft gage, the point of observation for tests following test 28 being at hole 12, see Fig. 21, page 85. For test preceding test 29 the observation was taken at the turn in the breeching.

Item 13. Average draft pressure in furnace, in. of water. Taken by means of an Ellison differential draft gage of $\frac{1}{2}$ in. range, graduated to $\frac{1}{400}$ of 1 in. For the majority of the tests readings were taken at two points, 21 and 22, Fig. 21 and 22, the gages being connected up differentially to holes 27 and 26, respectively, so that the averages tabulated are actual net pressures on the fuel bed.

Item 15. Average temperature of external air, degrees Fahrenheit, obtained from the record of a Bristol recording thermometer.

Item 16. Average temperature of boiler room, °F, obtained from the record of a Bristol recording thermometer.

Item 21. Average temperature of the escaping flue gases; F.°
 Readings for the flue gas temperatures during tests 1 to 27 were taken by means of a single high grade mercury thermometer inserted at the base of the breeching in a position which was supposed to be average. The data are retained in the table but they are unreliable. For tests 28 to 37 the temperature data are the average of three high grade Jena borosilicate glass thermometers located in the sampling section above the mixing baffles. Fig. 23. In the tests following test 37 temperature measurements

were taken by means of five copper-constantan thermo-couples distributed in the sampling section.

Items 85, 86, and 88. Analysis of dry flue gases. For tests No. 1 to 27 the gas samples were drawn from a single tube, extending centrally across the base of the breeching. This tube was made up of $\frac{1}{2}$ -in. pipe capped at one end and perforated with three rows of $\frac{1}{8}$ -in. holes spaced 3 in. apart. The results from the analyses of samples taken from this tube are of uncertain accuracy for the reasons set forth on page 88, and with but few exceptions the tabulated percentages of carbon dioxide for those tests are probably too high. This was recognized at the time the tests were in progress, and for that reason it was considered useless to make more complete analyses until time should permit devising and installing improved means for taking the sample. During the temporary interruption of the work which occurred between the tests 27 and 28, opportunity permitted the introduction of the sampling arrangement, previously described, and all subsequent gas samples for the series were taken under those improved conditions.

The sampling tube or tubes in both types of samplers were connected with the sampling bench by a $\frac{1}{4}$ -in. lead tubing, through which a steady stream of gas was kept flowing by means of a larger sized Richards laboratory ejector. The sample for analysis was drawn from a tee connection in this tube. The usual arrangement of one-gallon side-necked aspirator bottles was used for collecting the sample and an average sample collected for each half hour during the test. In some of the earlier tests the samples were drawn for a longer period. Distilled water saturated with the flue gas was used in the collecting vessels.

The analyses throughout were made by means of an Orsat apparatus provided with a 100 cc. water jacketed burette with 25 cc. tube of special wide graduation, and the readings taken subsequently corrected to the true calibration of the burette, including a correction for the gas volume contained in the capillary tube between the 100 cc. mark and the drop tubes, the total correction necessary being between 0.1 and 0.2 of 1 cc. representing a percentage correction of about the same magnitude in the observed percentages of carbon dioxide and oxygen.

Item 77. Smoke observations—Ringelmann's numbers. The observations taken were recorded in No. 0, $\frac{1}{2}$, 1, 2, etc., no

attempt being made to judge shades varying between. The tabulated values, however, being the time average of all readings, result in fractional values. These should be interpreted as being simply greater or less than Ringelmann Chart No. 1 or No. 2 as the case may be, for example, test No. 44 shows 0.21 smoke. That is, the average smoke reading for this test was less than No. 1 Ringelmann.

To summarize these readings for the series; three tests show No. 1 smoke, 13 tests what may be called, on the average, a faint haze, and for the remainder, 48 tests, one could not tell from observation of the stack, that the plant was in operation.

Chemical Analyses:

The chemical analyses of the coal and of the "ash and refuse" were made in the University chemical laboratories, under the direction of Professor S. W. Parr.

The data obtained from the analyses were more elaborate than apply directly to the needs of this report, and, no doubt, will contribute to the accumulation of available data for a more general study of the chemical and physical properties of Illinois coal, a problem which is receiving the attention of Professor Parr in connection with the State Geological Survey. All chemical analyses were made in duplicate and in case of an occasional disagreement, the results were checked by a third determination. The results reported by the chemical laboratory were the average of two closely agreeing analyses.

The methods of analysis followed were: total moisture equals the per cent loss upon air drying plus the loss in drying in an air oven at 105° C.; proximate analyses, following the methods recommended by the Committee on coal analysis of the American Chemical Society*; sulphur by gravimetric method after fusion with sodium peroxide in the Parr calorimeter, nitrogen by the Kjeldahl method; total carbon and hydrogen by the usual combustion train method, carbon in the "ash and refuse" by difference after determining the moisture and ash contained, and the calorific value of the coal by means of a platinum lined Mahler-Atwater calorimeter.

Determinations regularly made upon each test sample of coal were moisture, ash, sulphur, nitrogen and the calorific value, and upon the "ash and refuse" sample, moisture, ash and carbon.

* Jour. Amer. Chem. Society, Vol. XXI, p. 1130.

Complete proximate and ultimate analyses were made upon two samples from each carload of coal tested. One of those samples was a regular test sample, the second a composite sample made up from the regular analytical samples in portions of each representing by weights the separate original weights of coal sampled.

These composite analyses are presented on pages 5 to 6 in connection with the description of the coal used.

Where complete analyses have been made of individual test samples, they are given in Tables 37, 38 and 39. Figures set in regular type indicate results from analyses of the individual test samples. The italicised figures are calculated values based upon the percentages of fixed carbon and volatile matter, total carbon, hydrogen and oxygen found in the composite sample and the percentages of moisture, ash, sulphur, and nitrogen found in the individual test samples, the principle being that the average chemical character of the "combustible" portion of the coal excluding sulphur will be approximately constant throughout the car. How nearly this was true will be seen by comparison of the values calculated for the combustible composition from the composite analyses, and the similar values for the individual samples, Table 39, making allowance in the comparison for any variation which occurs in the percentages of sulphur and nitrogen.

The method of calculating these figures is given below.

In these tables both analytical and calculated results for coal as fired or for moisture-free coal are given the regular A. S. M. E. code item numbers, while the similar items computed to the basis of combustible are distinguished by a decimal 1, suffixed. Similarly, to distinguish them in the formulas which follow, items relating to determinations made upon the composite samples are indicated by suffixing a decimal 2 to the regular A. S. M. E. code numbers.

TABLE 37. Proximate Analyses:

$$\text{Item 32. Fixed carbon} = \text{Item 32.2} \times \frac{100 - (\text{Item 34} + \text{Item 35})}{\text{Item 32.2} + \text{Item 33.2}}$$

= Item 32.2 $\times k$ (a constant). Item 34 and 35 are those values given in the same table. Items 32.2 and 33.2 may be taken from either Table 2, 3 or 4. Those from table 2 were used.

$$\text{Item 33. Volatile matter} = \text{Item 33.2} \times k.$$

TABLE 38. Ultimate Analyses of Moisture Free Coal
Item 37.

$Total\ carbon = Item\ 37.2 \times \frac{100 - Item\ 40 + Item\ 41 + Item\ 42}{Item\ 37.2 + Item\ 38.2 + Item\ 39.2}$
 $= Item\ 37.2 \times m.$ Item 40, 41 and 42 are those values given in the same table. Items 37.2, 38.2 and 39.2 may be taken from either Table 2, 3 or 4. Those from Table 2 were used.

Item 38. *Hydrogen* = Item 38.2 $\times m.$

Item 39. *Oxygen* = Item 39.2 $\times m.$

TABLE 39. Calorific Value and Ultimate Analyses of Combustible:

Item 59 and 51, *Calorific values, B. t. u.*

Item 37.1, 38.1, 39.1, 40.1 and 41.1 are calculated by multiplying the items of Table 38 by the factor $\frac{100}{100 - Item\ 42}$

TABLE 40. Furnace Conditions:

An explanation of the items contained in this table has been given on page 92.

TABLE 28 PRINCIPAL CONDITIONS

No.	Laboratory File No.	Date of Trial	Duration	Principal Conditions					
				Size of Coal (Commercial)	Condition of Coal	Thickness of Fuel Bed	Draft Pressure in Furnace Assigned	Furnace Control	Total Coal Fired per Sq. Ft. of Grate Area
1	2	3	4	5	6	7	8	9	10
	Code Item	1	2	23	23	81	13		
			Hr.	In.		In.	In.		Lb.
1	21—4.0703 W	Dec. 7, '06	8.17	$\frac{7}{8}$ — $\frac{3}{4}$	Washed	6	0.20		301
2	23— " "	Dec. 10, '06	6.08	" "	" "	5	0.16		209
3	24— " "	Dec. 11, '06	8.17	" "	" "	4	0.12		236
4	25— " "	Dec. 12, '06	7.97	" "	" "	7	0.25		291
5	26— " "	Dec. 13, '06	7.63	" "	" "	4	0.10		262
6	30—5.0602 W	Dec. 18, '06	8.00	$\frac{3}{4}$ — $\frac{1}{4}$	" "	4	0.10		209
7	31— " "	Dec. 19, '06	7.87	" "	" "	4	0.12		223
8	32— " "	Dec. 20, '06	5.55	" "	" "	5	0.11		144
9	34— " "	Jan. 10, '07	7.25	" "	" "	6	0.14		196
10	35— " "	Jan. 11, '07	8.13	" "	" "	7	0.17		209
11	36— " "	Jan. 12, '07	8.08	" "	" "	6	0.16		209
12	37—5.0200 W	Jan. 14, '07	6.43	$\frac{1}{4}$ —0	" "	5	0.29		196
13	39— " "	Jan. 17, '07	7.93	" "	" "	6	0.39		249
14	40— " "	Jan. 18, '07	7.78	" "	" "	6	0.45		249
15	41— " "	Jan. 21, '07	5.70	" "	" "	4	0.23		209
16	42— " "	Jan. 22, '07	5.10	" "	" "	4	0.29		183
17	43—4.0700 W	Jan. 23, '07	8.15	$\frac{7}{8}$ —0	" "	5	0.14		236
18	44— " "	Jan. 24, '07	8.07	" "	" "	5	0.14		236
19	45— " "	Jan. 25, '07	8.08	" "	" "	4	0.12		236
20	46— " "	Jan. 26, '07	7.90	" "	" "	6	0.16		236
21	47—6.0402 W	Jan. 28, '07	8.32	$\frac{3}{4}$ — $\frac{1}{4}$	" "	6	0.15		209
22	48— " "	Jan. 29, '07	8.25	" "	" "	7	0.14		196
23	49— " "	Jan. 30, '07	8.22	" "	" "	5	0.10		183
24	50— " "	Jan. 31, '07	8.32	" "	" "	4	0.90		209
25	51—5.1610 W	Feb. 1, '07	8.40	$1\frac{3}{4}$ —1	" "	6	0.13		196
26	52— " "	Feb. 2, '07	8.12	" "	" "	6	0.13		209
27	53—6.0402 W	Feb. 4, '07	8.40	$\frac{3}{4}$ — $\frac{1}{4}$	" "	6	0.13		209
28	93—5.1610 W	Apr. 26, '07	8.22	$1\frac{3}{4}$ —1	" "	7	0.15		196
29	94— " "	Apr. 27, '07	7.82	" "	" "	6	0.13		183
30	95— " "	Apr. 29, '07	8.07	" "	" "	5	0.11		196
31	96—7.1610—	Apr. 30, '07	8.25	" "	Unwashed	5	0.10		196
32	97— " "	May 1, '07	7.20	" "	" "	6	0.13		170

See Page 21, for Method of Furnace Control

TABLE 28 PRINCIPAL CONDITIONS (*Concluded*)

No.	Laboratory File No.	Date of Trial	Duration	Principal Conditions					
				Size of Coal (Commercial)	Condition of Coal	Thickness of Fuel Bed	Draft, Pressure in Furnace Assigned	Furnace Control	Total Coal Fired per Sq. Ft. of Grate Area
1	2	3	4	5	6	7	8	9	10
	Code Item	1	2	23	23	81	13		
			Hr.	In.		In.	In.		Lb.
33	98-7.1610-	May 2, '07	8.38	1 $\frac{3}{4}$ -1	Unwashed	7	0.15		209
34	99- "	May 3, '07	8.07	"	"	8	0.12		209
35	100- "	May 4, '07	6.80	"	"	6	0.17		196
36	101- "	May 6, '07	8.10	"	"	6	0.20		262
37	102-5.1006 W	May 7, '07	6.05	1 - $\frac{3}{4}$	Washed	5	0.10		144
38	104- "	May 8, '07	8.18	"	"	5	0.09		183
39	107- "	May 9, '07	8.10	"	"	6	0.12		183
40	109- "	May 10, '07	7.82	"	"	7	0.15		183
41	110- "	May 11, '07	7.55	"	"	6	0.15		223
42	112- "	May 13, '07	7.85	"	"	5	0.10		157
43	113- "	May 14, '07	7.30	"	"	6	0.19		223
44	114- "	May 15, '07	4.82	"	"	6	0.25		183
45	115-6.0200 W	May 16, '07	8.02	$\frac{1}{4}$ -0	"	4	0.23		157
46	116- "	May 17, '07	6.00	"	"	6	0.40		132
47	117- "	May 18, '07	6.68	"	"	6	0.43		165
48	118- "	May 20, '07	7.95	"	"	6	0.38		196
49	119- "	May 21, '07	7.38	"	"	6	0.32		144
50	120- "	May 22, '07	8.17	"	"	5	0.32		196
51	121- "	May 23, '07	8.00	"	"	5	0.37		196
52	122- "	May 24, '07	8.42	"	"	5	0.38		223
53	124-4.0300 W	May 27, '07	7.87	$\frac{3}{8}$ -0	"	5	0.34		262
54	125- "	May 28, '07	8.12	"	"	5	0.30		223
55	126- "	May 29, '07	6.00	"	"	5	0.38		200
56	127- "	May 30, '07	7.02	"	"	5	0.40		246
57	128-4.0703 W	May 31, '07	8.27	$\frac{7}{8}$ -%	"	5	0.13		236
58	129- "	June 1, '07	6.80	"	"	5	0.12		204
59	130- "	June 3, '07	7.25	"	"	5	0.10		157
60	131- "	June 4, '07	8.15	"	"	5	0.12		209
61	132- "	June 5, '07	8.73	"	"	5	0.14		241
62	133- "	June 6, '07	7.95	"	"	5	0.18		275
63	134- "	June 7, '07	7.37	"	"	5	0.16		251
64	135- "	June 8, '07	7.00	"	"	5	0.06		120

See Page 21, for Method of Furnace Control

TABLE 29 COAL AND ASH

No.	Laboratory File No.	Total Coal and Ash							Analyses of Ash and Refuse	
		Weight of Coal as Fired	Percentage of Moisture in Coal	Total Weight of Dry Coal Fired	Total Ash and Refuse	Total Dry Coal Minus Ash and Refuse	Total Combustible Consumed	Percent of Ash and Refuse Referred to Dry Coal	Carbon	Earthy Matter
1	2	3	4	5	6	7	8	9	10	11
	Code Item	25	26	27	28	30.1	30	31	44	45
		Lb.	%	Lb.	Lb.	Lb.	Lb.	%	%	%
1	21—4.0703 W	11500	18.38	9386	1386	8000	7878	14.80	45.15	54.85
2	23—	8000	18.63	6510	737	5773	5698	11.32	21.13	75.87
3	24—	9000	17.35	7438	911	6527	6407	12.25	29.66	70.34
4	25—	11100	19.11	8979	1040	7939	7849	11.58	23.48	76.52
5	26—	10000	18.71	8129	1046	7083	6965	12.87	26.13	73.87
6	30—5 0602 W	8000	12.24	7021	861	6160	6028	12.25	21.03	78.97
7	31—	8560	13.15	7382	999	6383	6277	13.53	34.98	65.02
8	32—	5500	12.48	4814	560	4254	4178	11.63	19.90	80.10
9	34—	7500	13.13	6515	686	5829	5723	10.53	14.75	85.25
10	35—	8000	11.30	7096	695	6401	6255	9.79	15.81	84.19
11	36—	8000	12.41	7007	716	6291	6221	10.22	19.56	80.44
12	37—5.0200 W	7500	15.80	6315	1117	5198	4960	17.69	38.51	61.49
13	39—	9500	14.59	8114	1248	6866	6526	15.38	34.52	65.48
14	40—	9500	16.20	7961	1177	6784	6436	14.78	29.84	70.16
15	41—	8000	14.40	6848	1388	5460	5226	20.27	43.90	56.10
16	42—	7000	17.84	5751	1162	5489	4408	20.21	43.97	56.03
17	43—4.0700 W	9000	18.68	7318	1117	6201	6203	15.26	27.44	72.56
18	44—	9000	19.32	7261	955	6306	6219	13.15	24.03	75.97
19	45—	9000	18.33	7350	1072	6278	6298	14.58	41.91	58.09
20	46—	9000	18.79	7309	936	6373	6259	12.81	23.01	76.99
21	47—6.0402 W	8000	10.72	7142	919	6223	6271	12.86	31.07	68.93
22	48—	7500	10.72	6696	636	6060	5999	9.50	20.28	79.72
23	49—	7000	11.32	6208	763	5445	5420	12.29	34.45	65.55
24	50—	8000	11.23	7102	952	6150	6211	13.40	29.42	70.58
25	51—5.1610 W	7500	11.43	6643	954	5689	5735	14.36	34.52	65.48
26	52—	8000	10.94	7125	912	6213	6237	12.80	27.37	72.63
27	53—6.0402 W	8000	10.21	7183	679	6504	6492	9.45	20.61	79.39
28	93—5.1610 W	7500	8.79	6841	757	6084	6074	11.07	14.92	85.08
29	94—	7000	8.06	6436	732	5704	5691	11.37	21.45	78.55
30	95—	7500	8.44	6867	853	6014	6045	12.42	21.70	78.30
31	96—7.1610 —	7500	7.14	6965	874	6091	6177	12.50	17.82	82.18
32	97—	6500	7.14	6036	684	5352	5196	11.33	17.87	82.13

TABLE 29 COAL AND ASH (*Concluded*)

No.	Laboratory File No.	Total Coal and Ash							Analyses of Ash and Refuse	
		Weight of Coal as Fired	Percentage of Moisture in Coal	Total Weight of Dry Coal Fired	Total Ash and Refuse	Total Dry Coal Minus Ash and Refuse	Total Combustible Consumed	Percent of Ash and Refuse Referred to Dry Coal	Carbon	Earthy Matter
1	2	3	4	5	6	7	8	9	10	11
	Code Item	25	26	27	28	30.1	30	31	44	45
		Lb.	%	Lb.	Lb.	Lb.	Lb.	%	%	%
33	98—7.1610—	8000	6.79	7457	879	6578	6548	11.79	16.38	83.62
34	99— “	8000	7.61	7391	949	6442	6480	12.84	16.15	83.85
35	100— “	7500	7.78	6916	835	6081	6172	12.07	16.18	83.82
36	101— “	10000	7.34	9266	1065	8201	8057	11.49	17.44	82.56
37	102—5.1006 W	5500	8.58	5028	488	4540	4517	9.70	13.81	86.19
38	104— “	7000	10.12	6292	675	5617	5578	10.73	15.11	84.89
39	107— “	7000	9.40	6342	667	5675	5669	10.52	14.88	85.12
40	109— “	7000	8.99	6371	717	5654	5684	11.25	14.40	85.60
41	110— “	8500	9.38	7703	848	6855	6782	11.01	13.61	86.39
42	112— “	6000	8.90	5466	692	4774	4849	12.66	14.47	85.53
43	113— “	8500	9.74	7672	845	6827	6821	11.01	14.95	85.05
44	114— “	7000	9.25	6353	718	5635	5539	11.30	14.90	85.10
45	115—6.0200 W	6000	13.94	5164	810	4354	4087	15.69	46.18	53.82
46	116— “	5053	13.97	4347	506	3841	3602	11.64	33.74	66.26
47	117— “	6300	21.49	4946	496	4450	4242	10.03	16.59	83.41
48	118— “	7500	18.52	6111	709	5402	5101	11.60	28.31	71.69
49	119— “	5500	17.34	4546	627	3919	3745	13.79	32.48	67.52
50	120— “	7500	19.27	6055	834	5221	4952	13.77	33.60	66.40
51	121— “	7500	19.63	6028	751	5277	4976	12.46	27.78	72.22
52	122— “	8500	19.49	6843	807	6036	5724	11.79	25.30	74.70
53	124—4.0300 W	10000	21.61	7839	1266	6573	6144	16.15	33.80	66.20
54	125— “	8500	21.72	6654	1021	5633	5207	15.34	32.84	67.16
55	126— “	7627	21.35	5999	864	5135	4748	14.40	33.77	66.23
56	127— “	9404	21.25	7406	1156	6250	5819	15.61	34.98	65.02
57	128—4.0703 W	9000	17.24	7448	759	6689	6539	10.19	25.75	74.25
58	129— “	7777	22.68	6017	534	5483	5375	8.88	15.65	84.35
59	130— “	6000	17.95	4923	726	4197	4354	14.75	18.81	81.19
60	131— “	8000	19.83	6414	629	5785	5688	9.81	17.87	82.13
61	132— “	9201	17.68	7574	733	6841	6709	9.68	19.69	80.31
62	133— “	10500	16.48	8770	845	7925	7828	9.64	18.84	81.16
63	134— “	9600	19.29	7748	763	6985	6912	9.85	19.20	80.80
64	135— “	4600	19.49	3703	414	3289	3300	11.17	14.59	85.41

TABLE 30 STEAM AND WATER BACK

No.	Laboratory File No.	Barometric Pressure	Steam				Water Back				
			Average Gage Pressure	Absolute Pressure	Quality		Total Weight of Water Used	Temperature of Inflow	Temperature of Outflow	Per cent of Total Heat Lost to Water Back	Water Equivalent Correction Factor
					Percentage of Moisture	Factor for Correction for Quality					
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item		11	11.1	54	56	a	b	c	d	e
		Lb.	Lb.	Lb.	%		Lb.	°F.	°F.	%	
1	21—4.0703 W	14.60	151.0	165.6	1.05	.9923	41186	55.0	82.7	1.02	1.0165
2	23—“	14.59	151.0	165.6	1.20	.9912	30916	57.0	94.0	1.41	1.0218
3	24—“	14.64	152.0	166.6	2.16	.9842	47405	57.0	92.0	1.81	1.0291
4	25—“	14.42	152.0	166.4	1.23	.9911	46244	56.0	85.0	1.20	1.0191
5	26—“	14.34	152.0	166.3	1.18	.9914	44462	57.0	97.6	1.82	1.0280
6	30—5.0602 W	14.67	152.0	166.7	2.34	.9828	62390	56.0	84.6	2.04	1.0316
7	31—“	14.51	151.3	165.8	2.10	.9846	46780	56.0	92.9	1.90	1.0291
8	32—“	14.32	151.4	165.7	2.91	.9787	38228	56.0	89.8	2.14	1.0334
9	34—“	14.29	150.5	164.8	1.88	.9856	35960	56.0	97.9	1.82	1.0298
10	35—“	14.40	150.0	164.4	1.70	.9876	43892	57.0	91.2	1.66	1.0270
11	36—“	14.50	150.0	164.5	1.59	.9884	37570	56.0	103.7	1.98	1.0317
12	37—5.0200 W	14.50	150.0	164.5	2.25	.9832	29500	57.0	98.2	1.71	1.0327
	38—“	14.43	150.6	164.4	1.70	.9876	38498	57.0	99.8	1.69	
13	39—“	14.40	150.0	164.4	2.00	.9854	43060	57.0	97.4	1.86	1.0354
14	40—“	14.38	150.0	164.4	1.87	.9863	39332	57.0	96.3	1.67	1.0314
15	41—“	14.53	150.0	164.5	1.75	.9872	23471	55.0	99.5	1.39	1.0260
16	42—“	14.65	150.0	164.7	2.15	.9843	26314	56.0	101.3	1.88	1.0349
17	43—4.0700 W	14.60	150.0	164.6	1.52	.9889	41543	56.0	105.8	2.34	1.0372
18	44—“	14.36	150.0	164.4	1.53	.9888	48059	56.0	106.7	2.73	1.0420
19	45—“	14.45	150.1	164.6	1.60	.9883	56481	56.0	96.2	2.52	1.0391
20	46—“	14.53	150.0	164.5	1.71	.9875	40416	55.0	113.0	2.61	1.0406
21	47—6.0402 W	14.60	150.0	164.6	1.60	.9883	52811	57.0	112.0	3.19	1.0471
22	48—“	14.48	150.0	164.5	1.95	.9857	65935	56.0	93.8	2.84	1.0433
23	49—“	14.55	150.0	164.6	1.80	.9868	45114	57.0	119.4	3.58	1.0521
24	50—“	14.40	150.0	164.4	0.74	.9946	65277	56.5	97.2	2.96	1.0431
25	51—5.1610 W	14.43	150.0	164.4	0.80	.9942	56076	56.8	102.4	3.04	1.0467
26	52—“	14.39	150.0	164.4	0.75	.9945	69329	56.4	92.4	2.76	1.0423
27	53—6.0402 W	14.48	147.0	161.5	0.67	.9951	63780	54.7	93.8	2.65	1.0410
28	93—5.1610 W	14.39	149.9	164.3	1.00	.9927	73131	56.1	81.2	2.08	1.0323
29	94—“	14.38	152.8	167.2	1.00	.9927	150302	56.3	69.9	2.48	1.0389
30	95—“	14.27	150.0	164.3	1.00	.9927	53404	57.3	94.5	2.27	1.0355
31	96—7.1610—	14.37	150.4	164.8	0.57	.9959	61215	55.8	85.6	2.02	1.0316
32	97—“	14.67	152.3	167.0	0.55	.9959	50718	56.1	91.7	2.19	1.0334

TABLE 30 STEAM AND WATER BACK (Concluded)

No.	Laboratory File No.	Barometric Pressure	Steam				Water Back				
			Average Gage Pressure	Absolute Pressure	Quality		Total Weight of Water Used	Temperature of Inflow	Temperature of Outflow	Percent of Total Heat Lost to Water Back	Water Equivalent Correction Factor
					Percentage of Moisture	Factor for Correction for Quality					
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item		11	11.1	54	56	a	b	c	d	e
		Lb.	Lb.	Lb.	%		Lb.	°F.	°F.	%	
33	98—7.1610—	14.40	150.3	164.7	0.57	.9959	57843	56.4	88.5	1.96	1.0306
34	99—	14.33	148.2	162.5	0.57	.9959	61228	56.8	83.5	1.73	1.0269
35	100—	14.44	148.2	162.6	0.57	.9959	54740	56.7	83.0	1.62	1.0258
36	101—	14.31	146.7	161.0	0.57	.9959	58320	56.5	87.8	1.59	1.0255
37	102—5.1006 W	14.31	147.8	162.1	0.57	.9959	52030	56.9	81.4	1.96	1.0282
38	104—	14.26	146.7	161.0	0.57	.9959	61168	56.6	86.2	2.24	1.0324
39	107—	14.29	147.5	161.8	0.57	.9959	77517	57.2	77.9	1.96	1.0290
40	109—	14.28	148.1	162.4	0.45	.9967	62528	56.8	81.0	1.84	1.0279
41	110—	14.36	148.5	162.9	0.45	.9967	78897	56.0	78.2	1.78	1.0264
42	112—	14.16	148.5	162.7	0.75	.9945	75948	57.6	80.1	2.44	1.0360
43	113—	14.64	148.7	163.3	0.57	.9959	67233	58.0	83.2	1.76	1.0264
44	114—	14.24	148.1	162.3	0.57	.9959	34393	57.0	86.3	1.28	1.0199
45	115—6.0200 W	14.32	147.1	161.4	0.57	.9959	44895	57.1	79.5	1.74	1.0337
46	116—	14.23	145.1	158.3	0.57	.9959	40410	57.0	76.4	1.56	1.0304
47	117—	14.26	145.5	159.8	0.57	.9959	43105	57.9	77.1	1.37	1.0251
48	118—	14.43	145.8	160.2	0.57	.9959	57240	57.7	79.3	1.70	1.0290
49	119—	14.44	146.3	160.7	0.57	.9959	62017	56.9	70.8	1.62	1.0298
50	120—	14.29	147.3	161.6	0.57	.9959	56761	57.0	82.6	2.08	1.0356
51	121—	14.26	146.3	160.6	0.57	.9959	65280	57.5	75.5	1.67	1.0285
52	122—	14.25	148.6	162.8	0.57	.9959	72134	57.6	77.0	1.73	1.0293
53	124—4.0300 W	14.38	149.0	163.4	0.57	.9959	72612	56.1	72.2	1.36	1.0233
54	125—	14.36	148.5	162.9	0.57	.9959	63312	57.0	76.6	1.71	1.0289
55	126—	14.31	149.2	163.5	0.57	.9959	64500	56.7	71.1	1.40	1.0238
56	127—	14.27	149.5	163.8	0.57	.9959	62100	57.0	73.7	1.28	1.0215
57	128—4.0703 W	14.22	148.6	162.8	0.57	.9959	94657	56.9	75.4	1.90	1.0272
58	129—	14.11	149.2	163.3	0.57	.9959	73984	56.7	76.2	1.89	1.0277
59	130—	14.21	149.1	163.3	0.57	.9959	71182	56.9	79.7	2.62	1.0381
60	131—	14.14	149.4	163.5	0.57	.9959	85371	57.0	77.4	2.16	1.0308
61	132—	14.28	149.4	163.7	0.57	.9959	86456	57.0	79.3	2.09	1.0296
62	133—	14.31	148.3	162.6	0.57	.9959	97785	57.3	76.8	1.76	1.0254
63	134—	14.17	148.3	162.5	0.57	.9959	69250	57.0	82.1	1.78	1.0257
64	135—	14.28	147.3	161.6	0.57	.9959	51450	57.7	90.4	3.58	1.0516

TABLE 31 WATER LOG DATA

No.	Laboratory File No.	Feed Water Weighed			Feed Water Corrections							
		Number of Tanks Weighed	Weight per Tank	Total Water Weighed	Water Gage		Feed Tank		Steam Pressure		Miscellaneous Corrections	Total Correction
					Reading at Start	Reading at Close	Level at Start	Level at Close	Start, Gage	Close, Gage		
1	2	3	4	5	6	7	8	9	10	11	12	13
			Lb.	Lb.	In.	In.	In.	In.	Lb.	Lb.	Lb.	Lb.
1	21—4.0703 W	75	801	60075	4.25	4.00	14.70	17.40	153	150		— 351
2	23—..	55	803	44165	5.60	1.20	25.20	25.00	150	151		+1056
3	24—..	61	804	49044	3.70	4.50	20.50	20.00	150	151		+ 184
4	25—..	77	803	61831	4.25	4.80	27.50	34.00	153	150		—1092
5	26—..	69	803	55407	4.00	3.10	31.75	28.70	151	147	406a	+ 223
6	30—5.0602 W	60	806	48360	5.00	2.50	29.00	28.00	153	153		+ 726
7	31—..	62	866	49972	5.50	4.75	35.00	26.00	154	151		+1468
8	32—..	42	806	33852	4.25	7.50	30.25	22.75	154	154		— 49
9	34—..	54	808	43632	6.00	4.25	24.50	25.25	150	149		+ 292
10	35—..	60	806	48360	5.25	6.00	22.75	24.75	149	150	300b	— 159
11	36—..	60	805	48800	3.75	3.25	26.25	22.75	153	148		+ 591
12	37—5.0200 W	40	806	32240	4.75	4.50	25.50	24.50	148	147		+ 196
13	39—..	53	806	42718	4.50	4.75	25.75	21.50	152	148		+ 241
14	40—..	52	806	41912	4.50	4.00	26.75	22.25	149	149		+ 772
15	41—..	44	806	35464	3.50	5.25	28.25	30.25	149	148		— 706
16	42—..	37	806	29822	5.25	5.75	22.25	26.00	152	150		— 240
17	43—4.0700 W	60	805	48300	3.75	4.50	24.00	22.75	147	147		+ 7
18	44—..	62	806	49972	4.50	5.25	23.25	20.50	150	150		+ 225
19	45—..	61	806	49166	5.00	5.00	29.50	20.75	152	151		+1266
20	46—..	61	806	49166	5.75	6.00	26.50	19.25	151	150	146c	+ 883
21	47—6.0402 W	66	805	53130	4.50	4.50	25.00	22.75	148	151	214c	+ 200
22	48—..	63	805	50715	4.50	6.00	26.00	27.50	147	149	301c	— 774
23	49—..	59	805	47495	4.75	5.50	26.25	27.00	146	145	510c	— 665
24	50—..	67	805	53935	4.80	6.50	27.00	27.30	152	149	494c	— 823
25	51—5.1610 W	52	805	47495	4.00	3.50	22.25	22.80	150	151	530c	— 344
26	52—..	63	806	50778	4.50	4.25	22.25	20.75	150	152	480c	— 61
27	53—6.0402 W	66	805	53130	4.25	4.50	25.25	25.50	149	151	781c	— 884
28	93—5.1610 W	61	807	49227	6.00	6.50	24.00	26.00	149	153		— 380
29	94—..	55	807	44385	7.00	5.00	29.00	26.00	148	150		+ 917
30	95—..	59	807	47613	4.00	3.50	28.00	25.00	152	150		+ 540
31	96—7.1610—	60	807	48420	7.00	5.75	29.00	23.80	150	151		+1054
32	97—..	53	807	42771	4.00	5.00	27.50	29.75	147	155		— 515

a. Leakage from Pump. b. Valve in weighing tank accidentally opened.

c. Leakage through Blow-off Valve.

TABLE 31 WATER LOG DATA (Concluded)

No.	Laboratory File No.	Feed Water Weighed			Feed Water Corrections							
		Number of Tanks Weighed	Weight Per Tank	Total Water Weighed	Water Gage		Level at Start		Steam Pressure		Miscellaneous Corrections	Total Correction
					Reading at Start	Reading at Close	Level at Start	Level at Close	Start, Gage	Close, Gage		
1	2	3	4	5	6	7	8	9	10	11	12	13
			Lb.	Lb.	In.	In.	In.	In.	Lb.	Lb.	Lb.	Lb.
33	98—7.1610—	64	807	51648	6.00	6.00	29.00	25.80	150	148	.....	+ 454
34	99— " "	65	807	52455	3.00	4.80	27.00	26.00	150	147	.....	— 291
35	100— " "	60	807	48420	3.25	5.50	29.00	28.50	145	153	.....	— 397
36	101— " "	77	807	62139	3.50	2.50	27.00	28.00	149	146	.....	+ 70
37	102—5.1006 W	48	807	38736	5.00	3.25	25.00	25.50	152	144	.....	+ 289
38	104— " "	58	807	46806	7.00	5.00	31.00	25.75	153	151	.....	+1218
39	107— " "	60	807	48420	3.00	4.00	26.00	29.00	147	139	.....	— 716
40	109— " "	58	807	46806	4.00	7.00	27.00	24.00	154	155	.....	— 256
41	110— " "	70	807	56490	5.50	3.50	28.00	28.00	156	148	.....	+ 410
42	112— " "	50	807	40350	2.25	1.75	28.00	30.00	145	141	.....	— 198
43	113— " "	68	807	54876	6.00	3.50	26.50	27.00	150	142	.....	+ 464
44	114— " "	55	807	44385	5.00	5.75	25.00	29.50	150	148	.....	— 842
45	115—6.0200 W	31	807	25017	5.00	3.50	26.50	24.50	150	148	.....	+ 628
46	116— " "	28	807	22596	5.00	5.50	24.00	27.00	141	152	.....	— 490
47	117— " "	34	807	27438	3.50	2.50	29.50	25.00	150	148	.....	+ 876
48	118— " "	46	807	37122	4.50	5.75	25.50	27.00	144	153	.....	— 457
49	119— " "	30	807	24210	6.75	4.50	28.00	27.00	147	150	.....	+ 688
50	120— " "	44	807	35508	3.50	4.00	27.50	29.50	151	147	.....	— 430
51	121— " "	44	807	35508	4.75	3.50	26.00	28.00	151	148	.....	— 17
52	122— " "	51	807	41157	6.50	4.50	25.00	28.50	145	150	.....	+ 14
53	124—4.0300 W	54	807	43578	4.00	3.50	27.00	30.00	141	146	.....	— 291
54	125— " "	46	807	37122	5.00	3.50	25.00	28.00	151	150	.....	— 93
55	126— " "	42	807	33894	5.50	3.75	23.50	28.00	154	146	.....	— 293
56	127— " "	51	807	41157	6.50	4.00	24.50	26.25	155	153	.....	+ 316
57	128—4.0703 W	68	807	54876	4.50	3.00	27.00	25.00	154	150	.....	+ 618
58	129— " "	57	807	45999	4.00	5.00	26.50	26.75	151	147	.....	— 292
59	130— " "	45	807	36315	5.00	4.50	27.17	26.00	148	146	.....	+ 274
60	131— " "	62	807	50034	1.75	6.25	25.00	27.50	149	154	.....	—1384
61	132— " "	68	807	54876	5.00	2.00	26.75	23.00	150	146	.....	+1221
62	133— " "	82	807	66174	2.00	5.00	25.00	24.00	150	148	.....	— 565
63	134— " "	70	807	56490	7.00	3.00	30.75	24.50	151	146	.....	+1808
64	135— " "	34	807	27438	5.50	3.25	27.50	27.00	148	150	.....	+ 609

TABLE 32 TOTAL WATER

No.	Laboratory File No.	Total Water							
		Temperature of Feed Water Entering Boiler	Total Weight of Water Fed to Boiler	Equivalent Water Fed to Boiler from and at 212° F.	Water Actually Evap. Corrected for Quality of Steam	Factor of Evaporation	Equivalent Evaporation from and at 212° F.		
							Performance	Compensated for Water Back	Total Loss of Evap. Charged to Water Back
1	2	3	4	5	6	7	8	9	10
	Code Item	20	57	58	59	60	61	61.1	f
		°F.	Lb.	Lb.	Lb.		Lb.	Lb.	Lb.
1	21—4.0703 W	56.0	59724	72326	59274	1.2110	71781	72365	1184
2	23— ..	55.5	45321	54817	44828	1.2122	54340	55525	1184
3	24— ..	56.0	49228	59630	48450	1.2113	58688	60395	1707
4	25— ..	57.0	60739	73512	60198	1.2103	72858	74249	1391
5	26— ..	57.0	55630	67329	55152	1.2103	66750	68619	1869
6	30—5.0602 W	56.0	49086	59458	48242	1.2113	58436	60283	1847
7	31— ..	56.0	51440	62284	50647	1.2108	61323	63087	1784
8	32— ..	56.0	33803	40946	33083	1.2113	40073	41411	1338
9	34— ..	56.0	43924	53183	43291	1.2108	52417	53979	1562
10	35— ..	58.0	48201	58261	47603	1.2087	57538	59091	1553
11	36— ..	57.0	48891	59143	48324	1.2097	58458	60311	1853
12	37—5.0200 W	57.0	32436	39238	31891	1.2097	38579	39840	1261
13	39— ..	57.5	42959	51950	42332	1.2093	51192	53004	1812
14	40— ..	57.8	42684	51600	42101	1.2089	50896	52494	1598
15	41— ..	56.0	34758	42085	34313	1.2108	41546	42626	1080
16	42— ..	56.0	29582	35812	29118	1.2106	35250	36480	1230
17	43—4.0700 W	56.0	48307	58490	47771	1.2108	57841	59992	2151
18	44— ..	56.0	50197	60779	49635	1.2108	60098	62622	2524
19	45— ..	56.0	50432	61063	49842	1.2108	60349	62708	2559
20	46— ..	55.5	50049	60624	49423	1.2113	59866	62296	2430
21	47—6.0402 W	56.0	53330	64572	52706	1.2108	63816	66822	3006
22	48— ..	56.5	49941	60439	49227	1.2102	59575	62154	2579
23	49— ..	56.5	46830	56669	46212	1.2101	55921	58834	2913
24	50— ..	56.0	53112	64250	52825	1.2097	63902	66656	2754
25	51—5.1610 W	57.0	47151	57015	46878	1.2092	56685	59332	2647
26	52— ..	56.5	50717	61378	50438	1.2102	61040	63622	2582
27	53—6.0402 W	54.8	52246	63296	51990	1.2115	62986	65568	2582
28	93—5.1610 W	56.5	48847	59115	48490	1.2102	58683	60578	1895
29	94— ..	57.1	45302	54820	44971	1.2101	54419	56535	2116
30	95— ..	56.3	48153	58289	47801	1.2105	57863	59917	2054
31	96—7.1610 —	56.1	49474	59893	49271	1.2106	59647	61531	1884
32	97— ..	56.7	42256	51155	42083	1.2106	50945	52646	1701

TABLE 32 TOTAL WATER (Concluded)

No	Laboratory File No.	Total Water							
		Temperature of Feed Water Entering Boiler	Total Weight of Water Fed to Boiler	Equivalent Water Fed to Boiler from and at 212° F.	Water Actually Evap. Corrected for Quality of Steam	Factor of Evaporation	Equivalent Evaporation from and at 212° F.		
							Performance	Compensated for Water Back	Total Loss of Evap. Charged to Water Back
1	2	3	4	5	6	7	8	9	10
	Code Item	20	57	58	59	60	61	61.1	f
		°F.	Lb.	Lb.	Lb.		Lb.	Lb.	Lb.
33	98—7.1610—	56.5	52102	63059	51888	1.2103	62800	64721	1921
34	99—	56.8	52164	63092	51950	1.2095	62833	64523	1690
35	100—	56.7	48023	58093	47821	1.2097	57849	59341	1492
36	101—	56.6	62209	75254	61948	1.2097	74938	76349	1911
37	102—5.1006 W	57.0	39025	47193	38861	1.2093	46995	48320	1325
38	104—	56.6	48024	58090	47827	1.2096	57851	59725	1874
39	107—	56.7	47704	57698	47504	1.2095	57456	59122	1666
40	109—	57.0	46550	56298	46396	1.2094	56111	57676	1565
41	110—	56.9	56900	68532	56712	1.2097	68605	70416	1811
42	112—	57.5	40152	48536	39931	1.2088	48269	50006	1737
43	113—	57.9	55340	66878	55113	1.2085	66604	68362	1758
44	114—	57.0	43543	52657	43364	1.2093	52440	53483	1043
45	115—6.0200 W	57.0	25645	31010	25540	1.2092	30883	31923	1040
46	116—	57.0	22106	26724	22015	1.2089	26614	27423	809
47	117—	57.9	28314	34206	28198	1.2081	34066	34921	855
48	118—	58.0	36665	44291	36515	1.2080	44110	45389	1279
49	119—	58.0	24898	30079	24796	1.2081	29956	30848	892
50	120—	57.6	35078	42395	34934	1.2086	42221	23724	1503
51	121—	58.0	35491	42877	35345	1.2081	42700	43917	1217
52	122—	58.0	41143	49717	40974	1.2084	49513	50963	1450
53	124—4.0300 W	56.9	43287	52360	43109	1.2096	52145	53360	1215
54	125—	57.6	37029	44761	36877	1.2088	44577	45865	1288
55	126—	57.0	33601	40640	33463	1.2095	40473	41436	963
56	127—	57.1	41473	50157	41302	1.2094	49951	51024	1073
57	128—4.0703 W	57.3	55494	67092	55266	1.2090	66817	68634	1817
58	129—	57.0	45707	55283	45520	1.2095	55056	56581	1525
59	130—	57.0	36589	44254	36439	1.2095	44073	45751	1678
60	131—	57.0	48650	58842	48451	1.2095	58601	60406	1805
61	132—	57.0	56097	67855	55867	1.2096	67577	69577	2000
62	133—	58.0	65609	79275	65340	1.2083	78950	80955	2005
63	134—	58.0	58298	70441	58059	1.2083	70153	71955	1802
64	135—	59.0	28047	33856	27932	1.2071	33717	35456	1739

TABLE 33 FUEL AND WATER PER HOUR

No.	Laboratory File No.	Fuel per Hour				Water per Hour				
		Dry Coal Fired	Combustible Consumed	Dry Coal Fired per Sq. Ft. of Grate Surface	Combustible Consumed per Sq. Ft. of Water Heating Surface	Evaporated—Corrected for Quality of Steam	Equivalent Evaporation from and at 212° F.			
							Total	Per Square Foot of Water Heating Surface	Total	Per Sq. Ft. of Water Heating Surface
1	2	3	4	5	6	7	8		10	11
	Code Item	46	47	48	49	62	63	64	63.1	64.1
		Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
1	21—4.0703 W	1148	964	30.05	0.475	7255	8786	4.33	8931	4.40
2	23—	1070	937	28.05	0.462	7373	8937	4.41	9132	4.51
3	24—	910	784	23.83	0.387	5930	7183	3.54	7392	3.64
4	25—	1127	985	29.50	0.486	7553	9141	4.51	9315	4.60
5	26—	1065	913	27.88	0.450	7228	8748	4.32	8993	4.44
6	30—5.0602 W	878	754	22.98	0.372	6030	7304	3.60	7535	3.71
7	31—	938	798	24.56	0.394	6438	7795	3.85	8022	3.96
8	32—	867	753	22.70	0.371	5961	7221	3.56	7462	3.68
9	34—	899	789	23.52	0.389	5971	7230	3.57	7445	3.67
10	35—	872	769	22.84	0.379	5853	7074	3.49	7265	5.58
11	36—	867	770	22.69	0.380	5980	7234	3.57	7463	3.68
12	37—5.0200 W	982	771	25.69	0.380	4957	5997	2.96	6193	3.05
13	39—	1023	823	26.78	0.406	5336	6453	3.18	6681	3.29
14	40—	1023	827	26.78	0.408	5409	6539	3.22	6744	3.32
15	41—	1201	917	31.45	0.452	6020	7289	3.60	7478	3.69
16	42—	1128	864	29.53	0.426	5710	6912	3.41	7153	3.53
17	43—4.0700 W	898	761	23.51	0.375	5861	7097	3.50	7361	3.63
18	44—	900	771	23.57	0.380	6154	7451	3.68	7764	3.83
19	45—	909	779	23.80	0.384	6166	7466	3.69	7758	3.83
20	46—	925	792	24.22	0.391	6256	7579	3.74	7886	3.89
21	47—6.0402 W	859	754	22.48	0.372	6339	7675	3.79	8036	3.97
22	48—	812	727	21.25	0.359	5967	7221	3.56	7536	3.71
23	49—	756	660	19.78	0.325	5624	6806	3.36	7160	3.53
24	50—	854	747	22.35	0.368	6351	7683	3.79	8014	3.95
25	51—5.1610 W	791	683	20.70	0.337	5581	6748	3.33	7063	3.48
26	52—	878	768	22.98	0.379	6213	7519	3.71	7837	3.86
27	53—6.0402 W	855	773	22.88	0.381	6189	7498	3.70	7805	3.85
28	93—5.1610 W	833	739	21.79	0.365	5901	7142	3.52	7372	3.63
29	94—	823	728	21.55	0.359	5753	6962	3.43	7232	3.56
30	95—	851	749	22.28	0.370	5926	7174	3.54	7428	3.66
31	96—7.1610—	844	738	22.10	0.364	5972	7230	3.57	7458	3.68
32	97—	838	732	21.90	0.356	5845	7076	3.49	7312	3.61

TABLE 33 FUEL AND WATER PER HOUR (Concluded)

No.	Laboratory File No.	Fuel per Hour				Water per Hour				
		Dry Coal Fired	Combustible Consumed	Dry Coal Fired per Sq. Ft. of Grate Surface	Combustible Consumed per Sq. Ft. of Water Heating Surface	Evaporated—Corrected for Quality of Steam	Equivalent Evaporation from and at 212° F.			
							Total	Per Square Foot of Water Heating Surface	Compensated for Water Back	Per Sq. Ft. of Water Heating Surface
1	2	3	4	5	6	7	8	9	10	11
	Code Item	46	47	48	49	62	63	64	63.1	64.1
		Lb.	Lb.	Lb.	Lb.	Lb	Lb.	Lb.	Lb.	Lb.
33	98—7.1610—	890	781	23.28	0.385	6190	7491	3.70	7720	3.81
34	99— “	916	803	23.98	0.396	6494	7789	3.84	7998	3.94
35	100— “	1017	894	26.62	0.441	7032	8507	4.20	8726	4.31
36	101— “	1144	995	29.90	0.491	7648	9251	4.57	9487	4.68
37	102—5.1006 W	831	747	21.75	0.368	6424	7768	3.83	7987	3.94
38	104— “	769	682	20.13	0.336	5844	7070	3.49	7299	3.60
39	107— “	783	700	20.49	0.345	5885	7093	3.50	7298	3.60
40	109— “	815	727	21.34	0.359	5935	7178	3.54	7378	3.64
41	110— “	1020	898	26.70	0.443	7510	9084	4.48	9324	4.60
42	112— “	696	608	18.23	0.300	5086	6149	3.03	6370	3.14
43	113— “	1051	934	27.51	0.461	7550	9124	4.50	9365	4.62
44	114— “	1319	1150	34.54	0.568	9002	10886	5.37	11102	5.47
45	115—6.0200 W	644	510	16.86	0.251	3186	3852	1.90	3982	1.96
46	116— “	725	600	18.97	0.296	3670	4436	2.19	4571	2.25
47	117— “	740	635	19.37	0.313	4219	5097	2.51	5225	2.57
48	118— “	769	642	20.12	0.316	4593	5549	2.74	5710	2.82
49	119— “	616	507	16.12	0.250	3358	4057	2.00	4177	2.06
50	120— “	741	606	19.41	0.299	4277	5170	2.55	5354	2.64
51	121— “	754	622	19.73	0.307	4418	5338	2.63	5490	2.70
52	122— “	813	680	21.28	0.335	4864	5883	2.90	6055	2.98
53	124—4.0300 W	996	781	26.08	0.385	5479	6628	3.27	6782	3.34
54	125— “	820	642	21.46	0.316	4543	5492	2.71	5651	2.79
55	126— “	1000	791	26.17	0.390	5577	6745	3.32	6905	3.40
56	127— “	1055	829	27.62	0.409	5886	7119	3.51	7272	3.58
57	128—4.0703 W	901	791	23.58	0.390	6685	8082	3.98	8302	4.09
58	129— “	885	790	23.16	0.390	6694	8096	3.99	8320	4.10
59	130— “	679	601	17.77	0.296	5026	6079	3.00	6311	3.11
60	131— “	787	698	20.60	0.344	5945	7190	3.54	7411	3.65
61	132— “	867	768	22.70	0.379	6397	7738	3.82	7967	3.93
62	133— “	1103	985	28.87	0.486	8219	9931	4.90	10183	5.02
63	134— “	1052	938	27.55	0.463	7881	9523	4.70	9768	4.82
64	135— “	529	471	13.85	0.233	3990	4817	2.38	5065	2.50

TABLE 34 HORSE POWER AND ECONOMIC RESULTS

No.	Laboratory File No.	Horse Power		Economic Results							
		Developed	Percentage of Builders Rating Developed	Performance				Compensated for Water Back			
				Apparent Evaporation per pound of Coal as Fired	Equivalent Evaporation from and at 212° F.			Apparent Evaporation per Pound of Coal as Fired	Equivalent Evaporation from and at 212° F.		
					Per Pound of Coal as Fired	Per Pound of Dry Coal	Per Pound of Combustible		Per Pound of Coal as Fired	Per Pound of Dry Coal	Per Pound of Combustible
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item	65	67	68	69	70	71	65.1	69.1	70.1	71.1
		H. P.	%	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
1	21—4.0703 W	254.7	121.3	5.19	6.24	7.65	9.11	5.28	6.34	7.78	9.26
2	23—	259.0	123.3	5.65	6.79	8.35	9.54	5.77	6.94	8.53	9.75
3	24—	208.2	99.1	5.47	6.52	7.89	9.16	5.63	6.71	8.12	9.43
4	25—	265.0	126.2	5.47	6.56	8.11	9.28	5.57	6.69	8.26	9.46
5	26—	253.6	120.8	5.56	6.68	8.21	9.58	5.72	6.87	8.44	9.85
6	30—5.0602 W	211.7	100.8	6.14	7.30	8.32	9.69	6.33	7.53	8.58	10.00
7	31—	225.9	107.6	6.05	7.21	8.31	9.77	6.23	7.42	8.55	10.05
8	32—	209.3	99.7	6.15	7.29	8.32	9.59	6.36	7.53	8.60	9.91
9	34—	209.6	99.8	5.86	6.99	8.05	9.16	6.03	7.20	8.30	9.43
10	35—	205.0	97.6	6.03	7.19	8.11	9.20	6.19	7.38	8.33	9.45
11	36—	209.7	99.9	6.11	7.31	8.34	9.40	6.30	7.54	8.60	9.70
12	37—5.0200 W	173.8	82.8	4.32	5.14	6.11	7.78	4.46	5.31	6.31	8.03
13	39—	187.0	89.0	4.52	5.39	6.31	7.84	4.68	5.62	6.53	8.12
14	40—	189.5	90.2	4.49	5.36	6.39	7.91	4.63	5.53	6.59	8.16
15	41—	211.3	100.6	4.34	5.19	6.07	7.95	4.45	5.32	6.23	8.16
16	42—	200.3	95.4	4.22	5.04	6.13	8.00	4.37	5.22	6.34	8.28
17	43—4.0700 W	205.7	98.0	5.37	6.43	7.90	9.32	5.57	6.67	8.17	9.67
18	44—	216.0	102.9	5.58	6.68	8.28	9.66	5.81	6.96	8.63	10.07
19	45—	216.4	103.0	5.60	6.71	8.21	9.58	5.82	6.97	8.53	9.95
20	46—	219.7	104.6	5.56	6.65	8.20	9.56	5.79	6.92	8.53	9.95
21	47—6.0402 W	222.5	106.0	6.67	7.98	8.94	10.18	6.98	8.36	9.36	10.66
22	48—	209.3	99.7	6.66	7.94	8.90	9.94	6.95	8.28	9.29	10.37
23	49—	197.3	94.0	6.69	7.99	9.01	10.32	7.04	8.41	9.48	10.86
24	50—	222.7	106.0	6.64	7.99	9.00	10.29	6.93	8.33	9.39	10.73
25	51—5.1610 W	195.6	93.1	6.29	7.56	8.53	9.88	6.58	7.91	8.93	10.33
26	52—	217.9	103.8	6.34	7.63	8.57	9.79	6.61	7.95	9.04	10.20
27	53—6.0402 W	217.3	103.5	6.53	7.87	8.77	9.70	6.80	8.19	9.13	10.10
28	93—5.1610 W	207.0	98.6	6.51	7.82	8.58	9.66	6.72	8.07	8.86	9.97
29	94—	201.8	96.1	6.47	7.77	8.46	9.56	6.72	8.07	8.79	9.93
30	95—	207.9	99.0	6.42	7.72	8.43	9.57	6.65	7.99	8.73	9.91
31	96—7.1610—	209.6	99.8	6.60	7.95	8.56	9.66	6.81	8.20	8.83	9.96
32	97—	205.1	97.7	6.50	7.84	8.44	9.80	6.72	8.10	8.72	10.13

TABLE 34 HORSE POWER AND ECONOMIC RESULTS (*Concluded*)

No.	Laboratory File No.	Horse Power		Economic Results							
		Developed	Percentage of Builders Rating Developed	Performance				Compensated for Water Back			
				Apparent Evaporation per pound of Coal as Fired	Equivalent Evaporation from and at 212° F.			Apparent Evaporation per pound of Coal as Fired	Equivalent Evaporation from and at 212° F.		
					Per Pound of Coal as Fired	Per Pound of Dry Coal	Per Pound of Combustible		Per Pound of Coal as Fired	Per Pound of Dry Coal	Per Pound of Combustible
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item	65	67	68	69	70	71	68.1	69.1	70.1	71.1
		H. P.	%	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
33	98—7.1610—	217.1	103.4	6.51	7.85	8.42	9.59	6.71	8.09	8.68	9.88
34	99— " "	225.8	107.5	6.52	7.85	8.50	9.70	6.70	8.06	8.73	9.96
35	100— " "	246.6	117.4	6.40	7.71	8.36	9.37	6.57	7.91	8.58	9.61
36	101— " "	268.1	127.7	6.22	7.49	8.09	9.30	6.38	7.68	8.30	9.54
37	102—5.1006 W	225.2	107.2	7.10	8.55	9.35	10.40	7.30	8.81	9.61	10.69
38	104— " "	204.9	97.6	6.86	8.26	9.19	10.37	7.08	8.53	9.40	10.71
39	107— " "	205.6	97.9	6.81	8.21	9.06	10.14	7.01	8.45	9.32	10.43
40	109— " "	208.1	99.1	6.65	8.02	8.81	9.87	6.85	8.24	9.06	10.15
41	110— " "	263.3	125.4	6.69	8.07	8.91	10.12	6.87	8.28	9.15	10.39
42	112— " "	178.2	84.9	6.69	8.04	8.83	9.95	6.93	8.33	9.15	10.31
43	113— " "	264.5	126.0	6.51	7.84	8.68	9.77	6.68	8.05	8.91	10.03
44	114— " "	315.5	150.2	6.22	7.49	8.25	9.47	6.34	7.64	8.41	9.66
45	115—6.0200 W	111.7	53.2	4.27	5.15	5.98	7.56	4.41	5.32	6.18	7.81
46	116— " "	128.6	61.2	4.37	5.27	6.12	7.39	4.50	5.43	6.31	7.61
47	117— " "	147.7	70.3	4.49	5.41	6.89	8.03	4.60	5.55	7.06	8.23
48	118— " "	160.8	76.6	4.89	5.89	7.21	8.65	5.03	6.06	7.42	8.90
49	119— " "	117.6	56.0	4.53	5.45	6.59	8.00	4.67	5.61	6.79	8.24
50	120— " "	149.9	71.4	4.68	5.63	6.97	8.53	4.85	5.83	7.22	8.83
51	121— " "	154.7	73.7	4.73	5.69	7.08	8.58	4.87	5.85	7.28	8.82
52	122— " "	170.5	81.2	4.84	5.83	7.23	8.65	4.98	6.00	7.44	8.90
53	124—4.0300 W	192.1	91.5	4.33	5.22	6.65	8.48	4.43	5.34	6.81	8.68
54	125— " "	159.2	75.8	4.36	5.25	6.70	8.56	4.49	5.40	6.89	8.81
55	126— " "	195.5	93.1	4.41	5.30	6.74	8.52	4.51	5.42	6.90	8.82
56	127— " "	206.3	98.2	4.41	5.31	6.74	8.59	4.50	5.42	6.88	8.77
57	128—4.0703 W	234.3	111.6	6.17	7.43	8.97	10.21	6.34	7.63	9.23	10.49
58	129— " "	234.7	111.8	5.88	7.08	9.15	10.04	6.04	7.28	9.40	10.32
59	130— " "	176.2	83.9	6.10	7.35	8.95	10.12	6.33	7.63	9.29	10.51
60	131— " "	208.4	99.2	6.09	7.33	9.14	10.30	6.28	7.56	9.42	10.62
61	132— " "	224.3	106.8	6.10	7.35	8.92	10.07	6.28	7.57	9.18	10.37
62	133— " "	287.9	137.1	6.25	7.52	9.00	10.09	6.41	7.71	9.23	10.35
63	134— " "	276.0	131.4	6.07	7.31	9.05	10.15	6.23	7.50	9.28	10.41
64	135— " "	139.6	66.5	6.10	7.33	9.11	10.22	6.41	7.71	9.58	10.75

TABLE 35 EFFICIENCY AND COST OF EVAPORATION

No.	Laboratory File No.	Efficiency				Cost of Coal		
		"Boiler and Furnace"	Over-all	Compensated for Water Back		Per Ton of 3000 Pounds, Delivered	Used to Evaporate 1000 Pounds of Water Under Observed Conditions	Used to Evaporate 1000 Pounds of Water from and at 212° F.
				"Boiler and Furnace"	Over-all			
1	2	3	4	5	6	7	8	9
	Code Item	72	73	72.1	73.1	74	75.1	76.1
		%	%	%	%	Dollars	Dollars	Dollars
1	21—4.0703 W	61.76	57.25	62.78	58.19	1.00	0.095	0.079
2	23— " "	64.55	62.60	65.96	63.96	1.00	0.087	0.073
3	24— " "	62.13	59.61	63.94	61.34	1.00	0.090	0.075
4	25— " "	62.70	60.78	63.90	61.94	1.00	0.090	0.075
5	26— " "	64.97	62.53	66.79	64.28	1.00	0.088	0.074
6	30—5.0602 W	64.62	62.74	66.66	64.72	1.00	0.080	0.067
7	31— " "	65.22	61.80	67.12	63.60	1.00	0.081	0.068
8	32— " "	64.02	62.34	66.16	64.42	1.00	0.080	0.067
9	34— " "	61.11	60.08	62.93	61.87	1.00	0.084	0.070
10	35— " "	61.43	60.37	63.09	62.00	1.00	0.082	0.068
11	36— " "	62.40	60.98	64.38	62.91	1.00	0.080	0.067
12	37—5.0200 W	52.37	48.19	54.08	49.76	1.00	0.114	0.096
13	39— " "	52.61	49.39	54.47	51.14	1.00	0.108	0.091
14	40— " "	53.17	50.38	54.84	51.96	1.00	0.109	0.092
15	41— " "	53.49	47.93	54.88	49.17	1.00	0.114	0.095
16	42— " "	53.88	48.27	55.76	49.95	1.00	0.116	0.097
17	43—4.0700 W	62.97	60.00	65.31	62.23	1.00	0.091	0.076
18	44— " "	65.06	62.79	67.79	65.42	1.00	0.087	0.073
19	45— " "	64.52	62.26	67.04	64.69	1.00	0.087	0.073
20	46— " "	64.19	62.16	66.80	64.68	1.00	0.088	0.073
21	47—6.0402 W	67.73	64.79	70.92	67.84	1.00	0.073	0.061
22	48— " "	65.62	64.20	68.46	66.98	1.00	0.073	0.061
23	49— " "	68.66	65.49	72.24	68.90	1.00	0.072	0.060
24	50— " "	68.69	65.73	71.65	68.56	1.00	0.073	0.061
25	51—5.1610 W	65.12	61.60	68.16	64.47	1.00	0.077	0.064
26	52— " "	65.21	62.70	67.97	65.35	1.00	0.077	0.064
27	53—6.0402 W	64.60	63.25	67.25	65.84	1.00	0.074	0.062
28	93—5.1610 W	64.30	63.15	66.38	65.19	1.00	0.075	0.063
29	94— " "	63.80	62.10	66.28	64.52	1.00	0.075	0.063
30	95— " "	63.87	61.97	66.14	64.18	1.00	0.076	0.063
31	96—7.1610 W	63.88	62.42	65.90	64.00	1.00	0.074	0.062
32	97— " "	65.47	64.01	67.82	66.35	....	0.075	0.062

TABLE 35 EFFICIENCY AND COST OF EVAPORATION (Concluded)

No.	Laboratory File No.	Efficiency				Cost of Coal		
		"Boiler and Furnace"	Over-all	Compensated for Water Back		Per Ton of 2000 Pounds, Delivered	Used to Evaporate 1000 Pounds of Water Under Observed Conditions	Used to Evaporate 1000 Pounds of Water from and at 212° F.
				"Boiler and Furnace"	Over-all			
1	2	3	4	5	6	7	8	9
	Code Item	72	73	72.1	73.1	74	75.1	76.1
		%	%	%	%	Dollars	Dollars	Dollars
33	98—7.1610 —	64.01	62.64	65.97	64.56	1.00	0.075	0.062
34	99— " "	64.40	62.89	66.13	64.58	1.00	0.075	0.063
35	100— " "	62.86	61.54	64.48	63.12	1.00	0.077	0.064
36	101— " "	62.22	60.82	63.81	62.35	1.00	0.079	0.066
37	102—5.1006 W	69.62	68.62	71.58	70.55	1.00	0.069	0.057
38	104— " "	69.13	67.90	71.37	70.10	1.00	0.071	0.059
39	107— " "	67.68	66.50	69.64	68.42	1.00	0.072	0.059
40	109— " "	65.85	64.69	67.69	66.49	1.00	0.074	0.061
41	110— " "	67.47	66.33	69.25	68.08	1.00	0.073	0.061
42	112— " "	67.69	65.30	70.13	67.69	1.00	0.073	0.061
43	113— " "	66.71	65.46	68.47	67.19	1.00	0.075	0.063
44	114— " "	64.23	62.99	65.51	64.24	1.00	0.079	0.066
45	115—6.0200 W	51.62	47.27	53.36	48.86	1.00	0.115	0.095
46	116— " "	51.27	48.94	52.83	50.44	1.00	0.113	0.093
47	117— " "	54.49	53.46	55.86	54.80	1.00	0.110	0.091
48	118— " "	58.71	56.46	60.41	58.10	1.00	0.101	0.084
49	119— " "	54.30	51.49	55.92	53.02	1.00	0.109	0.090
50	120— " "	58.48	55.32	60.56	57.29	1.00	0.105	0.087
51	121— " "	58.63	56.25	60.30	57.86	1.00	0.104	0.086
52	122— " "	58.97	56.93	60.70	58.60	1.00	0.101	0.084
53	124—4.0300 W	58.37	54.61	59.73	55.88	1.00	0.114	0.095
54	125— " "	59.27	55.69	60.98	57.30	1.00	0.113	0.094
55	126— " "	58.75	55.37	60.15	56.68	1.00	0.112	0.093
56	127— " "	59.45	55.56	60.73	56.76	1.00	0.112	0.093
57	128—4.0703 W	69.98	68.00	71.88	69.85	1.00	0.080	0.066
58	129— " "	68.24	68.54	70.13	70.40	1.00	0.083	0.070
59	130— " "	68.81	66.69	71.43	69.23	1.00	0.080	0.064
60	131— " "	70.20	68.86	72.36	70.98	1.00	0.080	0.067
61	132— " "	68.68	67.25	70.71	69.24	1.00	0.080	0.067
62	133— " "	69.38	67.98	71.14	69.68	1.00	0.079	0.065
63	134— " "	69.36	67.82	71.14	69.66	1.00	0.081	0.067
64	135— " "	69.37	68.13	72.95	71.65	1.00	0.079	0.066

TABLE 36 AIR AND FLUE GASES

No.	Laboratory File No.	Air				Flue Gases					
		Average Draft Pressure in. Water		Average Temps.		Average Temperature of Escaping Flue Gases	Analysis of Dry Gases				Average Smoke Ringelmann Chart Number
		Between Damper and Boiler	In Furnace	External Air	Boiler Room		Carbon Dioxide	Oxygen	Carbon Monoxide	Nitrogen	
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item	12	13	15	16	21	84	85	86	88	77
				° F	° F	° F	%	%	%	%	
1	21—4.0703 W	.....	0.195	20.7	51.6	622	10.36				1.50
2	23— ..	.....	0.157	37.0	63.0	678	8.77				0.00
3	24— ..	.....	0.116	37.0	61.0	611	10.26				0.00
4	25— ..	.....	0.213	.....	.....	708	8.86				0.00
5	26— ..	.....	0.115	47.0	68.0	675	7.82				0.00
6	30—5.0602 W	0.254	0.102	33.0	61.0	639	7.04				0.00
7	31— ..	0.746	0.104	29.8	59.2	638	10.10				0.00
8	32— ..	0.324	0.040	31.0	61.0	650	9.54				0.00
9	34— ..	0.650	0.134	32.0	69.0	645	9.47				0.00
10	35— ..	0.715	0.162	34.0	61.0	642	6.22				0.08
11	36— ..	0.680	0.150	39.5	62.3	653	8.05				0.08
12	37—5.0200 W	0.880	0.270	38.0	60.7	641	7.10				0.00
13	39— ..	1.330	0.380	40.8	59.6	634	6.40				0.00
14	40— ..	1.440	0.430	39.0	62.1	626	5.84				0.00
15	41— ..	1.450	0.290	27.8	57.9	638	7.02				0.00
16	42— ..	1.420	0.270	.....	55.2	620	5.95				0.00
17	43—4.0700 W	0.450	0.130	22.2	51.0	586	10.50				0.00
18	44— ..	0.510	0.130	35.6	59.0	587	10.60				0.00
19	45— ..	0.460	0.106	18.6	66.3	589	11.20				0.00
20	46— ..	0.650	0.145	14.3	44.0	617	9.94				0.00
21	47—6.0402 W	0.420	0.127	28.0	54.9	599	12.40				0.00
22	48— ..	0.500	0.138	33.1	59.5	606	11.01				0.00
23	49— ..	0.350	0.105	31.2	58.2	583	11.79				0.00
24	50— ..	0.340	0.085	35.0	60.1	612	12.08				0.00
25	51—5.1610 W	0.400	0.122	39.2	64.3	615	10.30				0.00
26	52— ..	0.540	0.122	26.0	71.1	647	10.00				0.00
27	53—6.0402 W	0.540	0.122	21.0	51.6	648	9.60				0.00
28	93—5.1610 W	0.399	0.145	53.6	72.7	610	8.88	10.22	0	80.90	0.00
29	94— ..	0.375	0.124	60.7	72.9	608	8.88	10.25	0	80.87	0.00
30	95— ..	0.321	0.103	55.0	74.5	609	9.38	9.66	0	80.96	0.00
31	96—7.1610—	0.321	0.093	42.0	70.3	606	9.32	9.52	0	81.16	0.00
32	97— ..	0.311	0.124	53.4	70.7	600	9.00	9.89	0	81.11	0.00

TABLE 36 AIR AND FLUE GASES (Concluded)

No.	Laboratory File No.	Air				Flue Gases					
		Average Draft Pressure in. Water		Average Temps.		Average Temperature of Escaping Flue Gases	Analysis of Dry Gases				Average Smoke Ringelmann Chart Number
		Between Damper and Boiler	In Furnace	External Air	Boiler Room		Carbon Dioxide	Oxygen	Carbon Monoxide	Nitrogen	
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item	12	13	15	16	21	84	85	86	88	77
				° F	° F	° F	%	%	%	%	
33	98—7.1610—	0.354	0.143	62.1	71.5	611	9.40	9.43	0	81.17	0.00
34	99—	0.371	0.116	53.9	73.7	627	9.47	9.40	0	81.13	0.00
35	100—	0.508	0.157	50.7	72.3	655	9.52	9.28	0	81.20	0.00
36	101—	0.720	0.188	56.9	75.2	683	9.02	9.85	0	81.13	0.00
37	102—5.1006 W	0.266	0.097	65.2	74.9	617	10.56	8.00	0	81.44	0.00
38	104—	0.228	0.088	62.7	72.6	611	11.09	7.38	0	81.53	0.00
39	107—	0.250	0.113	76.3	80.3	599	10.79	7.55	0.01	81.65	0.00
40	109—	0.305	0.144	66.2	77.7	607	10.56	7.99	0.01	81.44	0.00
41	110—	0.404	0.146	54.7	74.1	670	11.48	7.34	0.01	81.17	0.00
42	112—	0.184	0.091	80.6	84.3	565	11.27	7.62	0	81.11	0.00
43	113—	0.500	0.174	73.4	82.9	676	11.12	7.78	0	81.10	0.11
44	114—	0.864	0.230	46.8	61.9	748	10.27	8.89	0	80.84	0.21
45	115—6.0200 W	0.560	0.165	54.8	70.3	562	4.62	15.28	0	80.10	0.00
46	116—	0.818	0.313	69.0	75.5	568	4.88	15.03	0	80.09	0.02
47	117—	0.893	0.414	75.4	80.8	581	5.53	14.24	0	80.23	0.00
48	118—	0.830	0.363	60.4	72.6	595	5.98	13.78	0	80.24	0.00
49	119—	0.624	0.303	58.3	67.9	556	5.11	14.71	0	80.18	0.00
50	120—	0.681	0.305	73.7	82.2	574	6.04	13.64	0	80.32	0.00
51	121—	0.862	0.346	82.0	86.9	576	5.87	13.83	0	80.30	0.02
52	122—	0.831	0.364	73.4	81.2	607	6.20	13.41	0	80.39	0.00
53	124—4.0300 W	0.845	0.339	54.2	73.1	622	6.56	12.97	0	80.47	0.00
54	125—	0.667	0.298	64.4	71.0	581	6.16	13.44	0	80.40	0.00
55	126—	0.891	0.367	67.3	74.9	610	6.58	12.93	0	80.49	0.00
56	127—	0.891	0.381	73.0	80.9	624	6.90	12.34	0	80.76	0.00
57	128—4.0703 W	0.303	0.132	57.6	72.2	618	11.08	7.52	0.01	81.39	0.16
58	129—	0.348	0.118	55.0	70.8	633	11.03	7.71	0	81.26	1.20
59	130—	0.150	0.096	67.4	73.3	533	12.50	6.13	0.01	81.36	0.10
60	131—	0.241	0.111	68.4	76.7	574	11.26	7.58	0	81.16	0.20
61	132—	0.325	0.137	69.5	79.0	604	10.98	7.78	0.01	81.23	0.15
62	133—	0.561	0.174	73.1	79.0	667	10.93	7.94	0	81.13	0.18
63	134—	0.495	0.161	66.1	75.6	665	11.18	7.61	0	81.21	0.23
64	135—	0.067	0.058	66.5	76.1	489	12.55	5.94	0.01	81.50	1.00

TABLE 37 PROXIMATE ANALYSES OF COAL

No.	Laboratory File No.	Proximate Analyses								
		Coal as Fired				Pure coal		Italicized Figures are Calculated from Analyses of Composite Samples Indicated	Referred to Combustible	
		Fixed Carbon	Volatile Matter	Moisture	Ash	Fixed Carbon	Volatile Matter		Moisture	Ash
1	2	3	4	5	6	7	8	9	10	11
	Code Item	32	33	34	35	32.1	33.1		34.1	35.1
		%	%	%	%	%	%	Chem. Lab.No. ^a	%	%
1	21—4.0703 W	41.48	32.46	18.38	7.68	56.10	43.90	Comp. No. 253	24.86	10.39
2	23—	41.21	32.24	18.63	7.92	56.10	43.90		25.36	10.72
3	24—	41.37	32.83	17.35	8.45	55.75	44.25		23.38	11.39
4	25—	40.90	32.01	19.11	7.98	56.10	43.90	Comp. No. 253	26.21	10.95
5	26—	40.60	31.78	18.71	8.91	56.10	43.90		25.85	12.31
6	30—5.0602 W	47.85	29.76	12.24	10.15	61.65	38.35	Comp. No. 272	15.77	13.08
7	31—	47.59	30.38	13.15	8.88	61.04	38.96		16.87	11.39
8	32—	48.05	29.91	12.49	9.55	61.65	38.35	Comp. No. 273	16.02	12.25
9	34—	47.87	29.78	13.13	9.22	61.65	38.35		16.91	11.87
10	35—	49.04	30.52	11.30	9.14	61.65	38.35		14.20	21.49
11	36—	49.28	30.28	12.41	8.08	61.92	38.08		15.61	10.16
12	37—5.0200 W	43.08	28.78	15.80	12.33	59.95	40.05	Comp. No. 303	21.98	17.16
13	39—	43.93	29.33	14.59	12.18	59.95	40.05		19.92	16.63
14	40—	42.82	28.61	16.20	12.36	59.95	40.05		22.68	17.30
15	41—	43.73	29.21	14.40	12.66	59.95	40.05		19.74	17.36
16	42—	42.13	28.14	17.84	11.89	59.95	40.05		25.39	16.92
17	43—4.0402 W	39.41	32.98	18.68	8.93	54.43	45.57	Comp. No. 302	25.80	12.34
18	44—	39.00	32.65	19.32	9.03	54.43	45.57		26.96	12.60
19	45—	40.81	34.16	18.33	6.70	54.43	45.57		24.45	8.94
20	46—	39.91	32.02	18.79	9.28	55.48	44.52		26.12	12.90
21	47—6.0402 W	49.52	32.45	10.72	7.31	60.41	39.59	Comp. No. 304	13.08	8.92
22	48—	50.12	31.58	10.72	7.58	61.35	38.65		13.12	9.28
23	49—	49.04	32.14	11.32	7.50	60.41	39.59	Comp. No. 304	13.94	9.24
24	50—	49.01	32.12	11.23	7.64	60.41	39.59		13.84	9.42
25	51—5.1610 W	54.05	26.80	11.48	7.72	66.85	33.15		14.14	9.55
26	52—	49.78	31.31	10.94	7.97	61.40	38.60	Comp. No. 502	13.49	9.83
27	53—6.0402 W	50.08	32.82	10.21	6.89	60.41	39.59	Comp. No. 304	12.32	8.31
28	93—5.1610 W	50.65	31.84	8.79	8.72	61.40	38.60	Comp. No. 502	10.66	10.57
29	93—	51.29	32.25	8.06	8.40	61.40	38.60		9.65	10.06
30	95—	51.01	32.07	8.44	8.48	61.40	38.60		10.16	10.21
31	93—7.1610	51.01	33.43	7.14	8.42	60.41	39.59		8.46	9.97
32	97—	50.06	31.76	7.14	11.04	61.18	38.82	Comp. No. 519	8.73	13.49

(a) For Analysis of the Composite Samples, see page 5.

TABLE 37 PROXIMATE ANALYSES OF COAL (*Concluded*)

No.	Laboratory File No.	Proximate Analyses								
		Coal as Fired				Pure Coal		Italicized Figures are Calculated from Analyses of Composite Samples Indicated	Referred to Combustible	
		Fixed Carbon	Volatile Matter	Moisture	Ash	Fixed Carbon	Volatile Matter		Moisture	Ash
1	2	3	4	5	6	7	8	9	10	11
	Code Item	32	33	34	35	32.1	33.1		34.1	35.1
		%	%	%	%	%	%	Chem. Lab.No.	%	%
33	98-7.1610-	51.18	32.47	6.79	9.56	61.18	38.82	Comp. No. 519	8.12	11.43
34	99- " "	50.73	32.10	7.61	6.47	61.18	38.82	" "	9.18	11.42
35	100- " "	51.45	32.64	7.78	8.13	61.18	38.82	" "	9.25	9.67
36	101- " "	50.44	31.99	7.34	10.23	61.18	38.82	" "	8.90	12.41
37	102-5.1008 W	52.02	31.31	8.58	8.09	62.43	37.57	.....	10.30	9.71
38	104- " "	50.68	30.46	10.12	8.74	62.46	37.54	Comp. No. 571	12.47	10.77
39	107- " "	51.46	30.93	9.40	8.21	62.46	37.54	" "	11.41	9.96
40	109- " "	51.64	31.03	8.99	8.34	62.46	37.54	" "	10.87	10.09
41	110- " "	50.66	30.46	9.38	9.50	62.46	37.54	" "	11.56	11.71
42	112- " "	51.53	30.97	8.90	8.60	62.46	37.54	" "	10.79	10.42
43	113- " "	51.04	30.69	9.74	8.53	62.46	37.54	" "	11.92	10.44
44	114- " "	50.37	30.28	9.25	10.10	62.46	37.54	" "	11.47	12.52
45	115-6.0200 W	46.56	27.79	13.94	11.71	62.62	37.38	.....	18.75	15.75
46	116- " "	46.60	28.07	13.97	11.36	62.41	37.59	Comp. No. 578	18.71	15.21
47	117- " "	42.84	25.80	21.49	9.87	62.41	37.59	" "	31.31	14.38
48	118- " "	44.12	26.58	18.52	10.78	62.41	37.59	" "	26.20	15.25
49	119- " "	44.81	26.99	17.34	10.86	62.41	37.59	" "	34.15	15.13
50	120- " "	43.53	26.22	19.27	10.98	62.41	37.59	" "	27.63	15.74
51	121- " "	43.14	25.99	19.63	11.24	62.41	37.59	" "	28.40	16.26
52	122- " "	43.52	26.22	19.49	10.77	62.41	37.59	" "	27.95	15.44
53	124-4.0300 W	36.65	29.07	21.61	12.67	55.77	44.23	.....	32.88	19.28
54	125- " "	36.47	28.73	21.72	13.08	55.94	44.06	Comp. No. 600	31.31	20.06
55	126- " "	36.96	29.11	21.35	12.58	55.94	44.06	" "	32.31	19.04
56	127- " "	37.02	29.15	21.25	12.58	55.94	44.06	" "	32.11	19.01
57	128-4.0703 W	42.94	31.89	17.24	7.93	57.39	42.61	.....	23.04	10.60
58	129- " "	39.56	30.64	22.63	7.17	56.35	43.65	Comp. No. 608	33.24	10.21
59	130- " "	42.17	32.67	17.95	7.21	56.35	43.65	" "	23.98	9.63
60	131- " "	41.60	30.89	19.83	7.68	56.39	42.61	.....	27.36	10.59
61	132- " "	41.97	32.51	17.68	7.84	56.35	43.65	Comp. No. 608	23.74	10.53
62	133- " "	42.82	33.24	16.48	7.46	56.30	43.70	.....	21.67	9.81
63	134- " "	41.43	32.09	19.29	7.19	56.35	43.65	Comp. No. 608	26.24	9.78
64	135- " "	41.62	31.43	19.49	7.46	56.98	43.02	.....	26.68	10.21

TABLE 38 ULTIMATE ANALYSES OF COAL

No.	Laboratory File No.	Ultimate Analyses of Moisture Free Coal						
		Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash	Italicized Figures Are Calculated from Analyses of Composite Samples Indicated
1	2	3	4	5	6	7	8	9
	Code Item	37	38	33	40	41	42	
		%	%	%	%	%	%	Chem. Lab. No.
1	21—4.0703 W	72.92	4.70	9.65	1.22	2.10	9.41	Comp. No. 253
2	23—“	72.48	4.68	9.59	1.22	2.29	9.74	“
3	24—“	72.00	4.95	9.37	1.22	2.24	10.32	“
4	25—“	72.51	4.68	9.59	1.25	2.10	9.87	Comp. No. 253
5	26—“	71.51	4.61	9.47	1.24	2.21	10.96	“
6	30—5.0602 W	72.51	4.61	8.47	1.35	1.50	11.56	Comp. No. 273
7	31—“	73.54	4.64	8.67	1.36	1.56	10.23	“
8	32—“	73.09	4.65	8.54	1.37	1.44	10.91	Comp. No. 273
9	34—“	73.40	4.67	8.56	1.38	1.38	10.61	“
10	35—“	73.48	4.68	8.58	1.47	1.49	10.30	“
11	36—“	74.37	4.44	9.34	1.35	1.28	9.22	“
12	57—5.0200 W	69.46	4.32	8.76	1.37	1.44	14.65	Comp. No. 303
13	39—“	69.81	4.34	8.81	1.39	1.39	14.26	Comp. No. 303
14	40—“	69.46	4.32	8.75	1.36	1.36	14.75	“
15	41—“	69.23	4.31	8.73	1.53	1.41	14.79	“
16	42—“	69.51	4.33	8.77	1.55	1.37	14.47	“
17	43—4.0700 W	70.29	4.60	10.50	1.50	2.07	11.04	Comp. No. 302
18	44—“	70.10	4.60	10.48	1.48	2.15	11.19	“
19	45—“	72.60	4.76	10.85	1.47	2.12	8.20	“
20	46—“	70.80	4.59	9.76	1.19	2.23	11.43	“
21	47—6.0402 W	74.72	4.77	9.08	1.68	1.56	8.19	Comp. No. 304
22	48—“	74.77	4.70	9.29	1.33	1.42	1.42	“
23	49—“	74.46	4.76	9.04	1.68	1.60	1.60	Comp. No. 304
24	50—“	74.39	4.76	9.03	1.68	1.54	1.54	“
25	51—5.1610 W	74.39	4.53	9.40	1.35	1.61	8.72	“
26	52—“	73.49	4.99	9.45	1.71	1.41	8.95	Comp. No. 502
27	53—6.0402 W	75.22	4.81	9.14	1.69	1.47	7.67	Comp. No. 304
28	93—5.1610 W	73.35	4.99	9.44	1.29	1.37	9.56	Comp. No. 502
29	94—“	73.66	5.01	9.47	1.31	1.41	9.14	“
30	95—“	73.59	5.00	9.47	1.30	1.38	9.26	“
31	96—7.1610 W	73.65	5.34	8.83	1.24	1.87	9.67	“
32	97—“	71.02	4.58	9.13	2.19	1.19	11.89	Comp. No. 519

TABLE 38 ULTIMATE ANALYSES OF COAL

No.	Laboratory File No.	Ultimate Analyses of Moisture Free Coal						
		Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash	Italicized Figures Are Calculated from Analyses of Composite Samples Indicated
1	2	3	4	5	6	7	8	9
	Code Item	37	38	39	40	41	42	
		%	%	%	%	%	%	Chem.Lab. No.
33	98—7.1610 —	71.88	4.62	9.23	1.21	2.79	10.27	Comp. No. 519
34	99— " "	72.35	4.67	9.31	1.37	2.05	10.25	" "
35	100— " "	73.53	4.74	9.45	1.38	2.09	8.81	" "
36	101— " "	71.18	4.59	9.15	1.33	2.71	11.04	" "
37	102—5.1006 W	74.43	5.04	8.91	1.42	1.36	8.84	.....
38	104— " "	72.97	4.61	9.73	1.45	1.52	9.73	Comp. No. 571
39	107— " "	73.70	4.65	9.83	1.47	1.29	9.06	" "
40	109— " "	72.60	4.64	9.81	1.46	1.33	9.16	" "
41	110— " "	72.44	4.57	9.66	1.40	1.40	10.48	" "
42	112— " "	73.47	4.63	9.79	1.43	1.23	9.45	" "
43	113— " "	73.44	4.63	9.73	1.36	1.33	9.45	" "
44	114— " "	72.06	4.55	9.60	1.34	1.32	11.13	" "
45	115—6.0200 W	70.15	4.48	8.95	1.20	1.61	13.61	Comp. No. 587
46	116— " "	70.27	4.39	9.36	1.08	1.70	13.21	.....
47	117— " "	70.77	4.41	8.41	1.22	1.62	12.57	" "
48	118— " "	70.20	4.38	9.34	1.21	1.64	13.23	" "
49	119— " "	70.31	4.39	9.35	1.21	1.61	13.13	" "
50	120— " "	69.99	4.37	9.30	1.18	1.56	13.60	" "
51	121— " "	69.55	4.33	9.25	1.19	1.69	13.99	" "
52	122— " "	70.12	4.38	9.32	1.21	1.60	13.37	" "
53	124—4.0300 W	66.47	4.47	9.28	1.17	2.45	16.16	.....
54	125— " "	66.89	4.39	8.47	1.09	2.45	16.71	Comp. No. 600
55	126— " "	67.53	4.43	8.55	1.11	2.39	15.99	" "
56	127— " "	67.51	4.44	8.55	1.09	2.43	15.98	" "
57	128—4.0703 W	77.91	4.69	10.44	1.23	2.15	9.58	.....
58	129— " "	72.55	4.82	10.33	1.20	1.84	9.28	Comp. No. 608
59	130— " "	73.00	4.85	10.39	1.25	1.73	8.78	" "
60	131— " "	72.02	5.11	10.25	1.20	1.85	9.57	.....
61	132— " "	72.23	4.80	10.28	1.22	1.95	9.52	Comp. No. 608
62	133— " "	72.83	4.84	10.36	1.21	1.83	8.93	" "
63	134— " "	72.84	4.84	10.37	1.24	1.81	8.90	" "
64	135— " "	72.66	4.77	10.24	1.23	1.83	9.27	.....

TABLE 39 ULTIMATE ANALYSES OF COMBUSTIBLE AND CALORIFIC VALUES

No.	Laboratory File No.	Ultimate Analyses of Pure Coal						Calorific Value by Oxygen Calorimeter	
		Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Italicized Figures Are Calculated from Analyses of Composite Samples Indicated	Per Pound of Moisture Free Coal	Per Pound of Combustible
1	2	3	4	5	6	7	8	9	10
	Code Item	37.1	38.1	39.1	40.1	41.1		50	51
		%	%	%	%	%	Chem. Lab. No.	B. t. u.	B. t. u.
1	21—4.0703 W	80.49	5.19	10.65	1.35	2.32	Comp. No. 253	12906	14247
2	23—	80.32	5.18	10.61	1.35	2.54	.....	12883	14273
3	24—	80.20	5.51	10.44	1.36	2.49	.....	12784	14239
4	25—	80.45	5.19	10.64	1.39	2.33	Comp. No. 253	12886	14295
5	26—	80.31	5.18	10.64	1.39	2.48	.....	12680	14241
6	30—5.0602 W	82.00	5.22	9.57	1.52	1.69	Comp. No. 273	12808	14483
7	31—	81.92	5.17	9.66	1.51	1.74	.....	12987	14467
8	32—	82.05	5.22	9.58	1.54	1.61	Comp. No. 273	12889	14468
9	34—	82.11	5.22	9.59	1.54	1.54	.....	12941	14477
10	35—	81.92	5.22	9.56	1.64	1.66	.....	12975	14465
11	36—	81.92	4.89	10.29	1.49	1.41	.....	13208	14549
12	37—5.0200 W	81.38	5.06	10.26	1.61	1.69	Comp. No. 303	12246	14348
13	39—	81.42	5.06	10.28	1.62	1.62	Comp. No. 303	12339	14391
14	40—	81.47	5.07	10.26	1.60	1.60	.....	12249	14368
15	41—	81.24	5.06	10.25	1.80	1.65	.....	12230	14353
16	42—	81.28	5.06	10.25	1.81	1.60	.....	12266	14341
17	43—4.0700 W	79.01	5.17	11.80	1.69	2.33	Comp. No. 302	12717	14295
18	44—	78.93	5.18	11.80	1.67	2.42	.....	12735	14340
19	45—	79.08	5.19	11.82	1.60	2.31	.....	12735	14340
20	46—	79.94	5.18	11.02	1.34	2.52	.....	12740	14384
21	47—6.0402 W	81.38	5.20	9.89	1.83	1.70	Comp. No. 304	13327	14516
22	48—	81.71	5.14	10.15	1.45	1.55	.....	13388	14630
23	49—	81.34	5.20	9.87	1.84	1.75	Comp. No. 304	13288	14516
24	50—	81.39	5.21	9.88	1.84	1.68	.....	13225	14469
25	51—5.1610 W	81.50	4.96	10.30	1.48	1.76	.....	13375	14653
26	52—	80.71	5.48	10.38	1.88	1.55	Comp. No. 502	13201	14499
27	53—6.0402 W	81.47	5.21	9.90	1.83	1.59	Comp. No. 304	13391	14503
28	93—5.1610 W	81.10	5.52	10.44	1.43	1.51	Comp. No. 502	13122	14509
29	94—	81.08	5.51	10.42	1.44	1.55	.....	13149	14472
30	95—	81.10	5.51	10.44	1.43	1.52	.....	13131	14471
31	96—7.1610 —	81.00	5.87	9.71	1.36	2.06	.....	13251	14573
32	97—	80.60	5.20	10.36	1.35	2.49	Comp. No. 519	12737	14456

TABLE 39 ULTIMATE ANALYSES OF COMBUSTIBLE AND CALORIFIC VALUES

No.	Laboratory File No.	Ultimate Analyses of Pure Coal						Calorific Value by Oxygen Calorimeter	
		Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	<i>Italicized Figures Are Calculated from Analyses of Composite Samples Indicated</i>	Per Pound of Moisture Free Coal	Per Pound of Combustible
1	2	3	4	5	6	7	8	9	10
	Code Item	37.1	38.1	39.1	40.1	41.1		50	51
		%	%	%	%	%	Chem. Lab. No.	B. t. u.	B. t. u.
33	98 ⁺ -7.1610 —	80.10	5.16	10.28	1.35	3.11	Comp. No. 519	12985	14470
34	99—	80.62	5.20	10.37	1.53	2.28	..	13057	14548
35	100—	80.63	5.21	10.37	1.51	2.29	..	13127	14395
36	101—	80.00	5.16	10.29	1.50	3.05	..	12842	14436
37	102-5.1006 W	81.65	5.53	9.77	1.56	1.49	.....	13152	14427
38	104—	80.83	5.10	10.77	1.61	1.69	Comp. No. 571	13077	14487
39	107—	81.05	5.11	10.80	1.62	1.42	..	13159	14470
40	109—	81.02	5.11	10.80	1.60	1.47	..	13151	14477
41	110—	80.92	5.11	10.78	1.62	1.57	..	12969	14487
42	112—	91.13	5.12	10.81	1.58	1.36	..	13062	14425
43	113—	81.10	5.11	10.81	1.51	1.47	..	12808	14145
44	114—	81.09	5.11	10.80	1.51	1.48	..	12655	14240
45	115-6.0200 W	81.20	5.19	10.36	1.39	1.86	.....	12220	14145
46	116—	80.97	5.06	10.76	1.25	1.96	Comp. No. 587	12081	13920
47	117—	80.94	5.05	10.76	1.39	1.86	..	12444	14233
48	118—	80.91	5.04	10.77	1.40	1.88	..	12345	14229
49	119—	80.94	5.06	10.76	1.39	1.85	..	12361	14229
50	120—	81.00	5.06	10.76	1.37	1.81	..	12171	14087
51	121—	80.86	5.04	10.76	1.37	1.97	..	12156	14133
52	122—	80.94	5.05	10.76	1.39	1.86	..	12272	14166
53	124-4.0300 W	79.29	5.33	11.07	1.39	2.92	.....	11764	14031
54	125—	80.30	5.28	10.17	1.31	2.94	Comp. No. 600	11617	13948
55	126—	80.39	5.27	10.18	1.32	2.84	..	11766	14005
56	127—	80.35	5.28	10.18	1.30	2.89	..	11724	13954
57	128-4.0703 W	79.53	5.19	11.54	1.36	2.38	.....	12740	14990
58	129—	79.96	5.31	11.38	1.32	2.03	Comp. No. 608	12893	14210
59	130—	80.03	5.32	11.039	1.37	1.89	..	12963	14212
60	131—	79.64	5.65	11.34	1.32	2.05	.....	12815	14171
61	132—	79.83	5.30	11.37	1.35	2.15	Comp. No. 608	12813	14161
62	133—	79.97	5.31	11.38	1.33	2.01	..	12791	14045
63	134—	79.96	5.31	11.38	1.36	1.99	..	12875	14133
64	135—	79.98	5.25	11.39	1.36	2.02	.....	12910	14229

TABLE 40 FURNACE CONDITIONS

No.	Laboratory File No.	Furnace Conditions During Test									
		Fuel at Rear of Grate				Fuel Bed for Four Hour Period		Area of Holes in Fuel Bed			Average Stoker Travel square feet per hour
		Per cent of Time			Average Distance Clear	Number of Times		Average	For 15 Min. Period		
		Banked	Close	Clear		Sliced	Leveled		Maximum	Minimum	
1	2	3	4	5	6	7	8	9	10	11	12
		Per cent			In.	No.	No.	Square inches		Sq. ft.	
1	21—.40703 W	23	50	27	6	...	2	0	0	0	65.5
2	23—	0	42	58	4½	1	0	0	0	0	68.8
3	24—	8	48	44	9½	1	0	0	0	0	67.9
4	25—	0	32	68	3	1	0	0	0	0	53.7
5	26—	0	7	93	3½	1	0	0	0	0	101.2
6	30—5.0602 W	0	20	80	4	1	0	0	0	0	75.1
7	31—	8	0	92	2	1	0	0	0	0	82.9
8	32—	0	47	53	3½	1	0	0	0	0	59.0
9	34—	0	48	52	8	1	0	0	0	0	50.9
10	35—	4	48	48	4½	1	0	0	0	0	42.4
11	36—	4	48	48	4½	1	0	0	0	0	49.1
12	37—5.0200 W	10	90	0	0	0	16	210	300	0	72.1
13	39—	5	20	75	7	0	6	100	300	0	53.1
14	40—	0	15	85	6½	0	15	150	400	150	64.0
15	41—	0	5	95	7	0	8	300	600	0	124.0
16	42—	0	5	95	8	0	9	100	400	0	128.4
17	43—4.0700 W	5	25	70	5	1	....	0	0	0	70.4
18	44—	8	3	89	6	1	0	0	0	0	72.4
19	45—	0	0	100	3½	1	0	0	0	0	92.4
20	46—	3	0	97	3	1	0	0	0	0	62.1
21	47—6.0402 W	0	0	100	4	1	30	0	0	0	51.0
22	48—	0	0	100	3	1	20	0	0	0	40.7
23	49—	0	12	88	3	1	20	0	0	0	53.7
24	50—	0	20	80	4	1	5	0	0	0	76.4
25	51—5.1610 W	0	64	36	4	1	8	0	0	0	46.9
26	52—	0	40	60	5	1	8	0	0	0	50.0
27	53—6.0402 W	0	12	88	5½	1	8	0	0	0	50.0
28	93—5.1610 W	0	0	100	3¾	1	6	0	0	0	40.2
29	94—	0	0	100	3½	2	6	3	100	0	46.8
30	95—	0	0	100	4	2	6	0	0	0	58.3
31	96—7.1610 —	0	0	100	3½	4	12	6	200	0	55.0
32	97—	0	0	100	3½	4	10	0	0	0	43.1

TABLE 40 FURNACE CONDITIONS (*Concluded*)

No.	Laboratory File No.	Furnace Conditions During Test									
		Fuel at Rear of Grate				Fuel Bed for Four Hour Period		Area of Holes in Fuel Bed			Average Stoker Travel square feet per hour
		Per cent of Time			Average Distance Clear	Number of Times		Average	For 15 Min. Period		
		Banked	Close	Clear		Sliced	Leveled		Maximum	Minimum	
1	2	3	4	5	6	7	8	9	10	11	12
		Per cent			In.	No.	No.	Square inches		Sq. ft.	
33	98—7.1610—	0	0	100	3½	5½	11	0	0	0	40.8
34	99— “	0	0	100	4	3	7	0	0	0	50.5
35	100— “	0	0	100	4¼	1	7	0	0	0	55.3
36	101— “	0	6	94	3	2	7	0	0	0	61.4
37	102—5.1006 W	0	0	100	4	2	9	0	0	0	55.4
38	104— “	0	0	100	4	3	8	0	0	0	52.8
36	107— “	0	0	100	3½	3½	11	0	0	0	42.8
40	109— “	0	0	100	3¾	3½	12	0	0	0	38.3
41	110— “	0	0	100	4	2	12	0	0	0	55.7
42	112— “	0	0	100	3¾	2	11	0	0	0	45.0
43	113— “	0	0	100	3½	1	12	0	0	0	56.7
44	114— “	0	0	100	3½	2	12	10.5	200	0	68.7
45	115—6.0200 W	0	0	100	5	0	18	22.0	500	0	85.7
46	116— “	0	0	100	4½	1	17	0	0	0	55.9
47	117— “	0	0	100	4¼	1	18	0	0	0	44.6
48	118— “	0	0	100	3¾	2	17	0	140	0	52.2
49	119— “	0	0	100	4¼	1½	16	2	50	0	44.4
50	120— “	0	0	100	4	1½	15	2	50	0	63.0
51	121— “	0	0	100	4½	1½	17	2	50	0	62.1
52	122— “	0	0	100	4	2	22	0	0	0	64.3
53	124—4.0300 W	0	0	100	4	1	16	0	0	0	87.8
54	125— “	0	0	100	4¼	1	15	0	0	0	69.6
55	126— “	0	0	100	3¾	1½	18	0	0	0	86.6
56	127— “	0	0	100	3½	2	21	0	0	0	89.3
57	128—4.0703 W	0	0	100	4	1	13	0	0	0	69.2
58	129— “	0	0	100	4	1½	6	0	0	0	75.2
59	130— “	0	0	100	4½	2	8	1.6	50	0	51.7
60	131— “	0	0	100	4	1½	10	0	0	0	59.8
61	132— “	0	0	100	4	1	10	0	0	0	64.5
62	133— “	0	0	100	4¼	1	11	0	0	0	85.3
63	134— “	0	0	100	3½	2	12	0	0	0	82.8
64	135— “	0	0	100	3½	2	7	0	0	0	38.7

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

- *Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904
- *Circular No. 1.* High-Speed Tool Steels, by L. P. Breckenridge. 1905.
- *Bulletin No. 2.* Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.
- *Circular No. 2.* Drainage of Earth Roads, by Ira O. Baker. 1906.
- Circular No. 3.* Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907, by L. P. Breckenridge and Paul Diserens. 1909.
- *Bulletin No. 3.* The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.
- *Bulletin No. 4.* Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.
- *Bulletin No. 5.* Resistance of Tubes to Collapse, by Albert P. Carman. 1906.
- *Bulletin No. 6.* Holding Power of Railroad Spikes, by Roy I. Webber. 1906.
- *Bulletin No. 7.* Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.
- *Bulletin No. 8.* Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906.
- *Bulletin No. 9.* An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.
- *Bulletin No. 10.* Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907.
- *Bulletin No. 11.* The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907.
- *Bulletin No. 12.* Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907.
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- *Bulletin No. 17.* The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1908.
- Bulletin No. 18.* The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1908.
- *Bulletin No. 19.* Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908.
- *Bulletin No. 20.* Tests of Concrete and Reinforced Concrete Columns, Series of 1907, by Arthur N. Talbot. 1908.
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- *Bulletin No. 22.* Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. 1908.
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- Bulletin No. 24.* The Modification of Illinois Coal by Low Temperature Distillation, by S. W. Parr and C. K. Francis. 1908.
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A STUDY IN HEAT TRANSMISSION

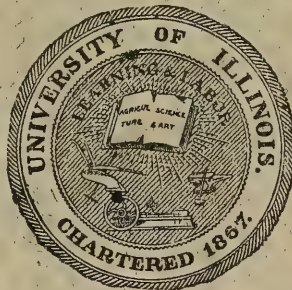
(THE TRANSMISSION OF HEAT TO WATER IN TUBES AS AFFECTED
BY THE VELOCITY OF THE WATER)

BY

J. K. CLEMENT

AND

C. M. GARLAND



UNIVERSITY OF ILLINOIS
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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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AFFECTED BY THE VELOCITY OF THE WATER)

BY

J. K. CLEMENT, PHYSICIST, U. S. G. S., TECHNOLOGIC BRANCH,

AND

C. M. GARLAND, INSTRUCTOR IN MECHANICAL ENGINEERING

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A STUDY IN HEAT TRANSMISSION

I. INTRODUCTION¹

The following experiments, preliminary in nature, were undertaken with two objects in view; (1) to determine the effect of the velocity of the flow of the water on the heat transmitted through the walls of tubes; (2) to determine if the methods of experimentation used were applicable and desirable for a more extensive investigation of the subject, provided this seemed justifiable by the results obtained.

In the flow of heat from a medium, gaseous or liquid, in contact with a metal plate, to a medium in contact with the opposite side of the plate, there are three resistances to be overcome; the two film resistances, that is, the resistance between the liquid and the plate on each side, and the resistance due to the metal of the plate. In the case of liquids in contact with metal plates, it will be found that the first two resistances are considerable as compared with the resistance of the plate itself, and also that these film resistances depend upon the nature of the medium in contact with the plate, and the relative movement or agitation between the plate and the medium. Owing, therefore, to the multiplicity of media and to the state of these media, as found in practice, it was considered advisable to endeavor to determine the rate of flow (or transmission) of heat as a function of the three factors, temperature of tube, temperature of water and velocity of water.

II. DESCRIPTION OF APPARATUS

The apparatus (Fig. 1) consisted of the steam jacket *F* provided with flanges and stuffing boxes at each end. The steam was admitted at *C* and bubbled up through the water in the jacket,

¹Acknowledgment.—Credit is due Mr. A. P. Kratz for assistance in the taking of readings and in making the computations.

which was kept at a constant level, and then passed out the exhaust at *D*. The pressure of the steam in the jacket, and therefore the temperature, was maintained constant by placing a safety valve on the exhaust pipe, and allowing the steam to blow through this valve throughout the tests. The bubbling of the steam through the water prevented the possibility of superheat due to throttling at the valve *C*.

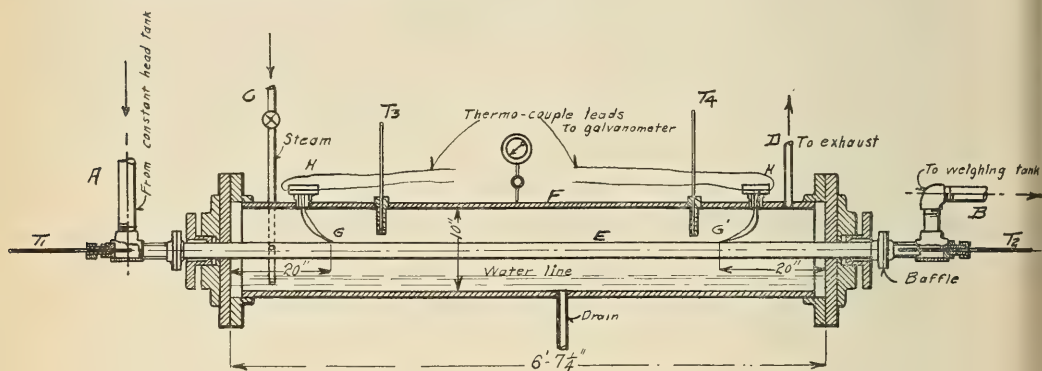


FIG I

TRANSMISSION OF HEAT THROUGH
BOILER TUBES

The tube through which the flow of heat was measured was a 1-in. Shelby cold-drawn steel tube, outside diameter 1.253 in.; inside diameter .985 in., and walls .134 in. thick. This tube was centered through the steam jacket, as shown, and packed around the ends. Each end was threaded, and a flange coupling used to connect the tube on the entering end with the water supply pipe *A*, and on the discharge end with the swinging ell at *B*. Rubber gaskets $\frac{1}{4}$ -in. thick were placed between these couplings; on the discharge end, a sheet metal baffle was inserted. Another baffle was inserted in the pipe *A* about 18 in. above the tee. The object of these baffles was to break up the stream lines before reaching the thermometers T_1 and T_2 . This was done in order that the average temperature of the water might be determined. The couplings were drawn together with insulated bolts. The insulation, together with the gaskets, was used to prevent the conduction of heat back on the tube. The water supply was taken from

a constant head tank, located about 25 ft. above the tube, which permitted a maximum velocity of about 17 ft. per second. The velocity through the tube was regulated to suit the demands by means of a throttle valve placed in the pipe *A*. The steam supply was taken from the laboratory mains.

III. MEASUREMENT OF TEMPERATURES

The temperature of the water, entering and leaving, was taken with mercury thermometers reading directly to tenths; these readings could be estimated to hundredths of degrees C. The thermometers were passed through the stuffing boxes and were in direct contact with the water. The baffles, above mentioned, insured the breaking up of the stream lines, so that very nearly the average temperature of the water was obtained. This was tested by changing the position of the thermometers.

The temperature of the steam was also taken with mercury thermometers T_3 and T_4 , passed through stuffing boxes, so that their bulbs were in direct contact with the steam. Allowance was made for the error due to the pressure of the steam on the bulb. The drawing shows these thermometers placed in thermometer cups; the cups, however, were taken out before the regular experiments were begun and replaced by stuffing boxes.

The temperature of the steam wall of the tube was taken by means of copper-constantan thermocouples and a Siemens and Halske millivoltmeter. The couples were located at G and G' , 20 in. from the face of each flange. The ends of the couples were soldered into small holes, about $\frac{1}{32}$ in. in diameter, and about $\frac{1}{4}$ in. deep, which were drilled in the surface of the tube. The leads were brought out through small glass tubing to the pipe flanges at HH , and then between two rubber gaskets placed between the flanges.

The mean temperature of the tube was taken as the average of the temperatures taken with the two couples, and is given in column 6 of Table 1. All readings were taken in Centigrade units and later changed to Fahrenheit.

TABLE 1

No.	Temperatures in Degrees F.										Water			Conductance		
	Entering Av.	Leaving Water Av.	Rise	Steam in Jacket	Steam Wall of Tube. Mean	Drop from Steam to Wall of Tube	Drop through Metal of Tube	Water Wall of Tube	Water in Tube. Mean	Drop from Wall of Tube to Water	Weight of Water per Minute	Velocity of Water in ft. per second	B. t. u. per sq. Minute	Conductance of Film on Steam Side	Conductance of Water Side	Conductance of Film on Water Side
1	56.92	66.75	9.83	210.9					61.8	318.0	16.07	1615				A
2	58.20	70.25	12.05	210.9					64.2	263.0	13.29	1638				
3	58.55	71.90	13.35	210.9					65.2	236.0	11.93	1628				C
4	58.63	73.20	14.57	210.9					65.9	204.3	10.93	1538				
5	58.20	74.82	16.62	210.9					66.5	176.0	8.90	1512				
6	57.89	75.28	17.39	210.9					66.6	147.0	7.43	1422				
7	58.20	78.52	20.32	210.9					68.4	120.0	6.07	1260				
8	58.29	84.49	26.20	210.9					71.4	81.1	4.11	1098				
9	58.37	92.00	33.63	210.9					75.2	55.1	2.80	957				
10	58.81	108.40	49.59	210.9					83.7	29.0	1.48	741				
11	60.10	175.49	115.40	210.9					117.8	7.12	.37	425				
1	58.55	73.35	14.80	273.6	181.2	92.4	35.2	146	65.9	80	331.7	16.78	2537	.458	.528		.367
2	58.32	78.12	19.80	274.4	202.0	72.4	34.7	167	68.2	99	244.4	12.37	2501	.576	.421	.312
3	58.15	75.45	17.30	273.7	193.2	80.5	36.5	157	66.8	90	294.3	14.89	2631	.544	.487	.347
4	57.90	80.94	23.04	273.9	203.0	70.9	33.1	170	69.4	100	200.5	10.15	2387	.561	.399	.300
5	58.03	85.83	27.80	274.1	208.0	66.1	31.0	177	71.9	105	155.7	7.89	2037	.561	.354	.273
6	58.10	92.88	34.78	274.1	211.0	63.1	28.9	182	75.5	108.5	116.0	5.88	2083	.550	.325	.256
7	62.87	120.46	57.59	274.1	235.0	39.1	23.8	211	91.7	119	57.6	2.94	1715	.730	.240	.200
8	63.28	108.50	45.22	274.5	227.0	47.5	24.8	202	86.0	116	76.4	3.89	1786	.698	.256	.211
9	63.73	145.90	82.17	274.5	239.7	34.8	21.0	219	105.0	114	35.7	1.84	1516	.724	.222	.187
10	67.55	162.20	94.65	274.5	243	31.4	19.0	224	114.0	110	28.0	1.45	1369	.724	.207	.177
1	67.54	85.00	17.46	306.6	219.9	86.7	43.6	176	76.3	100	348.4	17.64	3144	.605	.525	.365
2	67.54	87.19	19.65	306.6	219.0	87.6	43.2	176	74.4	102	306.4	15.50	3112	.591	.508	.357
3	67.54	93.30	25.76	306.5	230.5	76.1	41.6	189	80.4	109	326.0	11.43	2998	.655	.459	.333
4	58.73	107.69	48.96	306.8	246.4	60.4	36.7	210	83.2	127	104.7	5.33	2649	.731	.347	.269
5	58.89	118.05	59.16	307.0	252.3	54.7	34.7	217	88.5	129	81.8	4.17	2501	.761	.322	.254
6	59.27	129.70	70.43	307.0	255.7	51.3	31.3	224	94.5	129	62.0	3.17	2256	.731	.291	.234
7	59.52	154.35	94.83	307.4	261.1	46.3	28.8	232	107.0	125	42.5	2.19	2081	.750	.278	.226
1	57.67	80.50	22.83	330.2	220	110.2	55.2	165	69.0	96.0	338.4	17.13	3995	.606	.694	.440
2	57.67	83.88	26.21	330.0	229.4	100.6	52.0	177	70.8	106.0	277.4	14.05	3756	.621	.591	.386
3	58.28	90.92	32.64	330.0	233.1	96.9	47.8	185	74.6	110.0	205.0	10.39	3455	.594	.524	.365
4	58.17	97.90	39.73	330.2	241.8	88.4	45.1	197	78.07	119.0	158.7	8.06	3260	.614	.457	.331
5	58.50	120.60	62.10	330.2	257.4	72.8	37.0	220	89.5	130.5	83.3	4.25	2672	.611	.340	.265
6	58.89	161.50	102.61	330.2	267.1	63.1	32.8	234	110.2	124.0	44.7	2.31	2370	.635	.318	.231

IV. OBSERVATIONS

The velocity of the flow of the water through the tube was obtained by weighing the total amount discharged over a given period of time. This time was measured with a stop watch. In calculating the volume of water discharged, corrections were made for the different temperatures of this discharge.

Observations were taken over periods of from 3 to 12 minutes, depending upon the velocity of the water. During these periods, six readings of the thermometers were made, so that all of the temperatures given in Table 1 are the average of six readings. At the beginning of a period, an observer swung the end of the discharge pipe *B* over a tank previously balanced on a pair of platform scales, and at the same time snapped the stop watch. The temperatures were then read at equal intervals during the period. At the end of the period, the pipe *B* was swung from over the water tank.

Observations were taken for four different temperatures of the steam in the jacket, 210.9° , 274° , 307° , and 330° F., and for each jacket temperature the water velocity was varied from about .4 to 17 ft. per second. In these experiments, no attempt was made to keep the temperature difference constant between the steam in the jacket and the mean temperature of the water.

V. CALCULATIONS

Referring to Table 1, column 14, the British thermal units per square foot per minute have been computed from the weight of water per minute, column 12; the rise in temperature of the water, column 4; and the area of the tube, computed from the mean diameter.

The mean temperature of the water, column 10, is the average of the items of columns 2 and 3. The curves of Fig. 2 show that within the temperature range of these experiments, this will be the true mean value.

The formula for the flow of heat through a given medium is similar to that for the flow of an electric current, and may be obtained as follows:

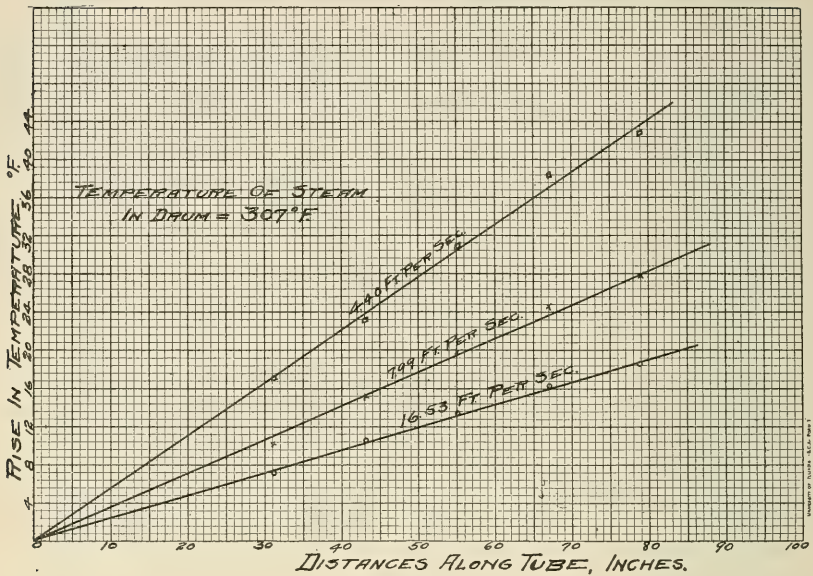


FIG. 2

Let Q = B. t. u. flowing per square foot per second.

$(t-t_1)$ = the temperature drop in degrees F. between two planes cutting the medium parallel to each other, and perpendicular to the direction of flow.

A = area in square feet of a section through which the heat is transmitted.

S = the time in seconds during which the flow takes place.

L = length in inches of the medium or the perpendicular distance between the two planes.

K = the conductivity of the medium, which is equal to the number of B. t. u. transmitted per second, per degree difference in temperature F., per square foot of area per inch of length.

Then
$$Q = \frac{(t-t_1) \times A \times S \times K}{L} \dots \dots \dots (1)$$

The quantity K has been determined experimentally by a number of experimenters, and in c. g. s. units is about .2 for boiler iron. Reducing this to B. t. u., square feet, degrees F., and inches, we obtain the value, .1612 = K = the conductivity of boiler iron. The reciprocal of the conductivity is equal to the specific

resistance =
$$\frac{1.0}{.1612} = 6.2$$

In the present case the thickness of the wall of the tube is .134 in. The resistance of the metal of the tube per square foot, therefore, = $6.2 \times .134 = .831$ and the "conductance" is

$$\frac{1.0}{.831} = 1.204. \quad \text{This value has been assumed to be constant}$$

for the temperatures here used.

It will be well to point out here the distinction between "conductivity" and "conductance", as used in the present article. Conductivity has been used to designate that quantity of heat which will flow through a medium of unit length and of unit area in a unit of time with a temperature drop of one degree, while "conductance" is independent of the length of the medium. The distinction is made necessary on account of the unknown thickness of the steam and water films.

The conductance of the water film, or the B. t. u. transmitted per square foot per second through this film may be determined in the following manner:

- Let Q = B. t. u. transmitted per square foot per second.
 A = area of the surface of the film in square feet.
 S = time in seconds.
 K'' = conductance of the water film.
 K''_1 = conductivity of the water film.
 L'' = thickness of water film, and can not readily be determined.
 $(t'' - t''_1)$ = drop in temperature between the inner or water surface of the tube and the water.

$$Q = \frac{K''_1 (t'' - t''_1) \times A \times S}{L''} \dots \dots \dots (2)$$

and

$$K'' = \frac{K''_1}{L''} = \frac{Q}{(t'' - t''_1) A \times S} \dots \dots \dots (3)$$

In order to determine $(t'' - t''_1)$, it will be necessary to determine the temperature of the inner or water surface of the tube. The temperature of the steam surface is given in Table 1, column 6. From formula 1, having Q , which is obtained from Table 1, column 14, and K , given, the temperature drop through the metal of the tube may be computed. This has been done and the results are given in column 8. By subtracting the temperature drop through the metal of the tube from the temperature of the

steam surface of the tube, the temperature of the water surface is obtained. This is given in column 9, and the drop from the water surface to the mean temperature of the water is given in column 11. Having this drop, the conductance of the water film may be computed from the formula.

A consideration of the phenomena occurring on the steam side of the tube is foreign to the purpose of this paper. As, however, the application of the results of experiments along this line have already proved of the greatest practical value in the design of high vacuum apparatus, and as our data are so closely related to this side of the problem, that is, the transmission of heat from the steam to the tube, it will probably not be amiss to devote a small amount of space to this phase of the subject.

On the steam side of the tube, if a condition of equilibrium is assumed to maintain, there will be the condition of saturated steam imparting its heat to a film of water on the surface of the tube, which film may be assumed to be of a constant thickness, and which is constantly being replaced or renewed by the condensation of fresh steam. The agitation of the steam in contact with the water film will, therefore, if it does not agitate this film, have no effect upon the rate of heat transmission or the conductance, at least, in the case of the present experiments; for the maximum velocity of approach of the steam towards the tube, due to the condensation, is about $\frac{1}{5}$ ft. per second. This would lead one to believe that the temperature on the surface of separation of the steam from the water film must be practically the temperature of the saturated steam. If such is the case, the agitation of the steam alone would not affect the conductance, as it would not change the temperature drop through the tube. The solution of the problem of more efficient heat transmission from steam to surface of tube, therefore, lies solely in the removal or agitation of the water film.

If it is then assumed that the temperature of the surface of water film in contact with the steam is at the temperature of the steam, and that the temperature of the surface of the water film in contact with the tube is at the temperature of the tube, the conductance of the water film on the steam side of the tube may be computed from the following:

Let $K' =$ conductance of the film.

$K'_1 =$ conductivity of the film.

L' = thickness of film in inches.

A = area of surface of film in square feet.

S = time in seconds.

Q = B. t. u. transmitted per square foot per second.

$(t' - t'_1)$ = temperature drop between steam in jacket and outer surface of tube, as obtained by thermocouples.

$$Q = \frac{K'_1 (t' - t'_1) A \times S}{L'} \dots \dots \dots (4)$$

therefore

$$K' = \frac{K'_1}{L'} = \frac{Q}{(t' - t'_1) \times A \times S} \dots \dots \dots (5)$$

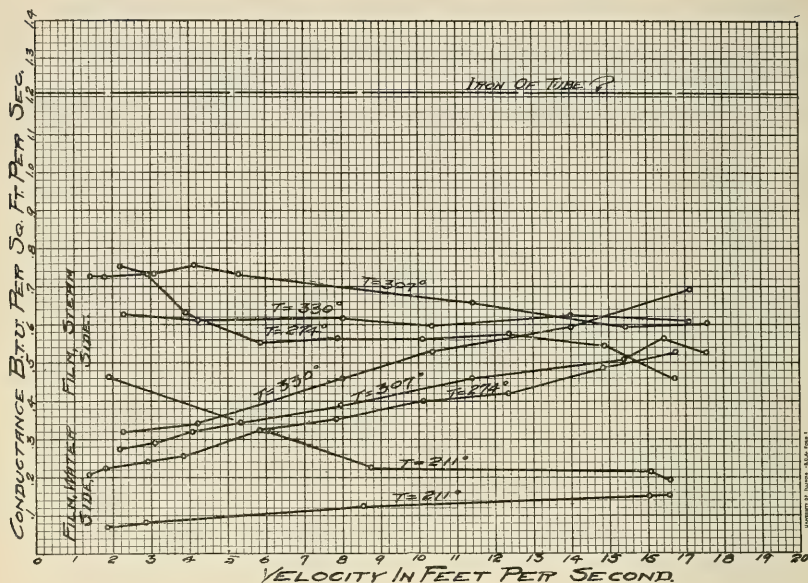
In the above formula A and S may be taken as unity; Q is obtained from Table 1, column 14; the values here given are expressed in B. t. u. per minute and must be reduced to B. t. u. per second before being used in the formula.

$(t' - t'_1)$ is taken from column 7 of the same table.

The value of L' can not be determined.

The conductances of the water films on the steam and water sides of the tube are given in columns 15 and 16, respectively, and these results are shown plotted against the velocity in feet per second of the water in the tube, Fig. 3. The temperatures placed on these curves are the temperatures in the steam jacket during each experiment. The data from which the points on the 211° curve were plotted were taken from the results of some later experiments, and have not been included in the table.

It will be seen from this figure, that the conductance of the film on the water side increases with the velocity of the flow of the water in the tube. This increased conductance at the higher velocities, which means a higher rate of agitation of the water, is due to the increased number of particles of the water coming in contact with the walls of the tube. The word "conductance" used to express the flow of heat from tube to water is somewhat inappropriate in this place, for it seems to suggest that the film remained the same so far as its physical structure was concerned, and that its heat conductivity varied, while as a matter of fact, the increased conductance or the increased flow of heat from the tube to the water at the higher velocities is due to the destruction or rather to the continuous renewal of this film. In the case of water flowing in a tube at velocities lower than the critical ve-



locity, where the stream lines are parallel, we can consider that this stream of water is made up of concentric cylinders of water, the central cylinder of which is moving at the highest velocity, and the velocity of the outer cylinders gradually drops off until the lowest velocity is found in that cylinder which is in direct contact with the walls of the tube. In this case, the heat flow from the walls of the tube takes place principally by conduction, and the effect of convection is very small. The case is analogous to that of heating water in a vessel from the top, such as has been used for the determination of the specific conductivity of water and other liquids. When the critical velocity of the water in the tube is reached, or when baffles are placed so as to disturb the parallelism of the stream lines, the concentric cylinders of water disappear and the stream lines mingle and flow from side to side in zigzag fashion; the film of water adjoining the tube walls is being continually renewed by these zigzag stream lines, and the flow of heat from tube to water is carried on largely by convection.

The conductance of the film on the steam side has been computed and the results are given in column 15 of the table. These conductances have also been plotted against the velocity of flow of the water in the tube and are shown in Fig. 3.

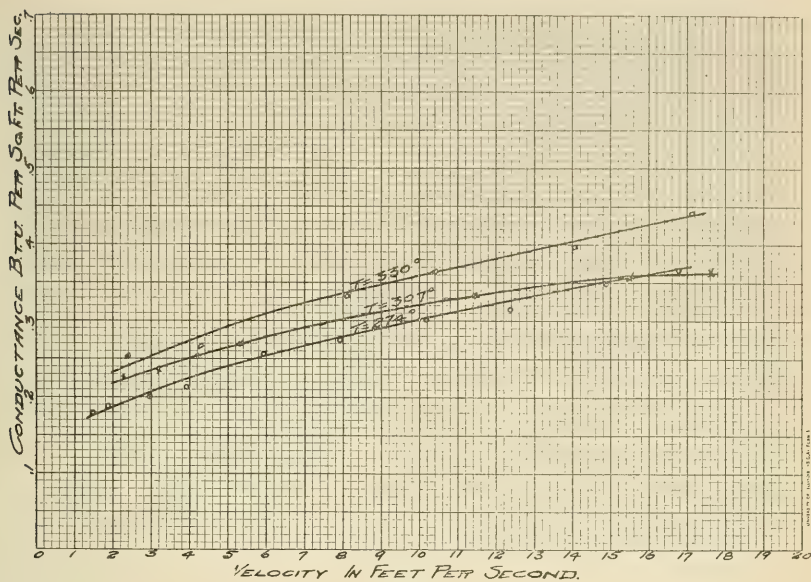


Fig. 4

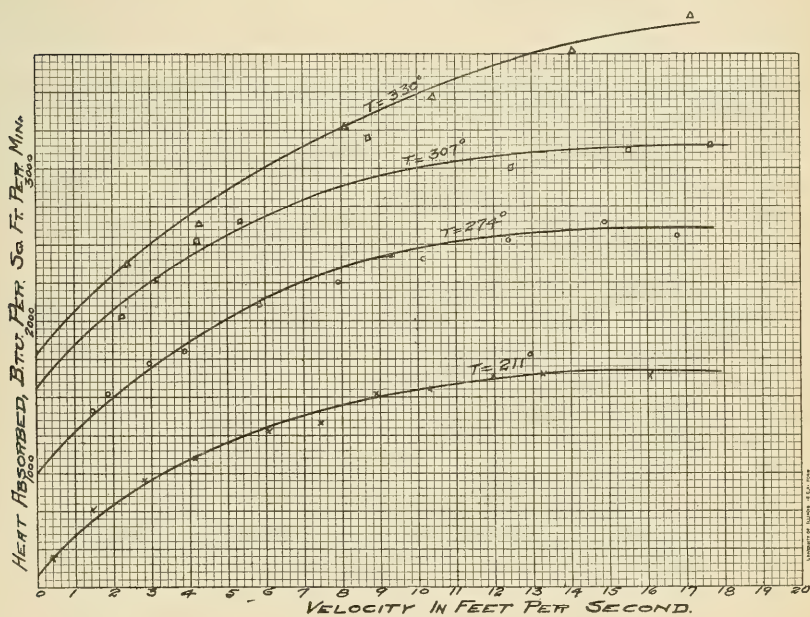


Fig. 5

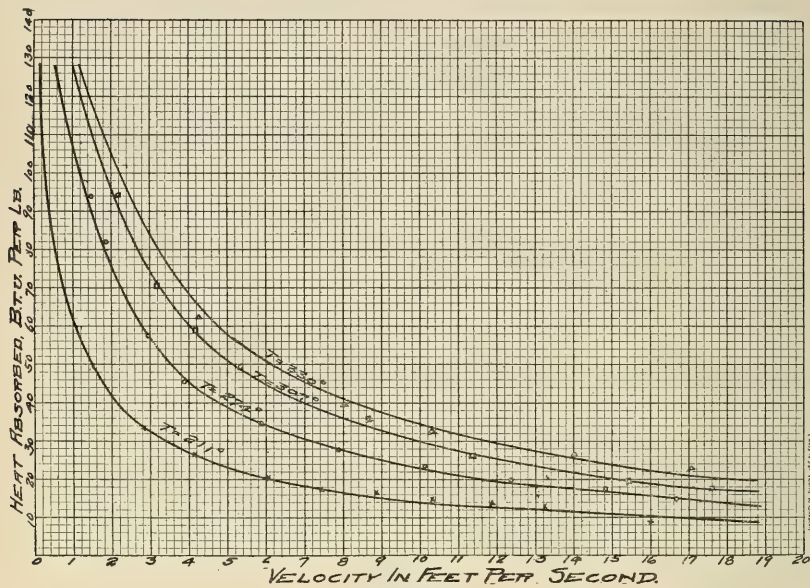


Fig. 6

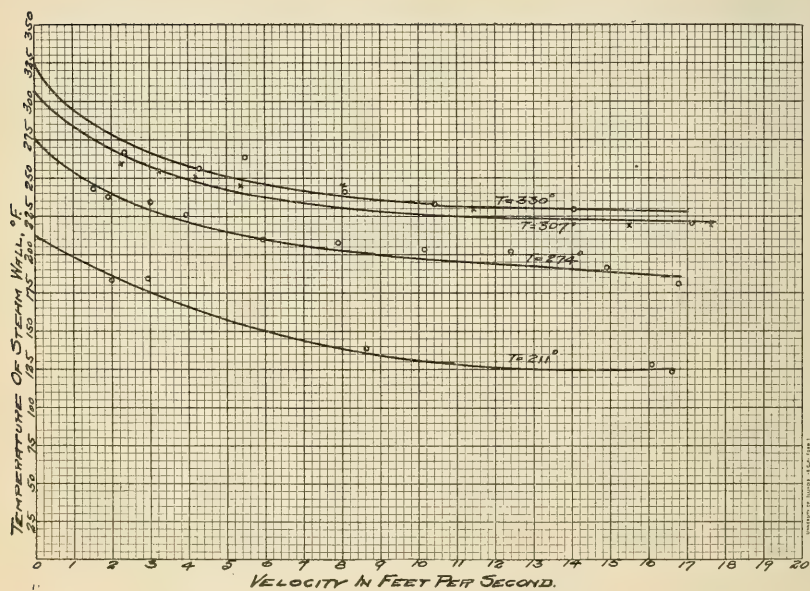


Fig. 7

It will be noted that the conductance of the steam film increases as the velocity of the water in the tube decreases. This is doubtless due to the decrease in temperature difference between the steam and the water as the velocity of the latter is decreased. This results in less condensation on the tube, consequently a thinner layer or water film on the surface of the tube, which makes a higher conductance possible.

The curve taken with a steam temperature of 330° in the jacket is almost a straight line. The other curves also tend to assume a straight line at the higher velocities, which means at the higher temperature differences. It is possible that the former curve would rise suddenly at the smaller velocities.

In Fig. 3 is also shown the straight dashed line indicating the constant conductance of the metal of the tube, which is 1.204.

In column 17 of the table, are given the conductances through tube and film on the water side. These were computed by taking the reciprocal of the sum of the reciprocals of the conductances of the tube and of the film on the water side; the former of which is constant and equal to 1.204, while the latter is obtained from column 16 of the table. The conductances of tube and film are shown in Fig. 4 plotted against the velocity of flow of the water.

The curves of Fig. 5 show the relation between the velocity of the flow of the water in the tube and the total heat transmitted per minute per square foot of mean tube surface. Curves of Fig. 6 show the relation between the velocity of the water and the B. t. u. absorbed per pound. The curves of Fig. 2 were obtained by a set of separate experiments to investigate the rise in temperature of the water along the tube. The temperatures in the tube were taken by means of a thermocouple placed in the end of a long glass tube which was pushed through a perforated cork placed in the end of the water or boiler tube. Beyond the end of the glass tube and ahead of the thermocouple junction, a small baffle was placed so that the mean temperature of the water might be obtained. It will be seen that the rise in temperature is proportional, within the limits of these experiments, to the distance from the entering end of the tube.

In Fig. 7, the temperature of the steam surface of the tube is plotted against velocity of water in feet per second. These curves by their uniformity seem to indicate the reliability of this method of experimentation.

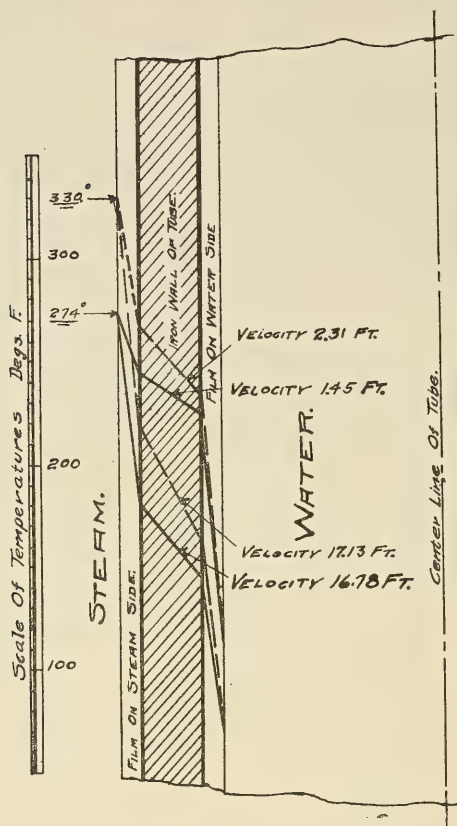


FIG. 8

Fig. 8 is a graphical representation of the temperature gradient through the film on the steam side, the tube and the film on the water side. The values corresponding to the maximum and the minimum velocities, as obtained in the experiment, have been plotted for the steam temperatures of 330° and 274° maintained in the jacket. Fig. 8 illustrates the increased temperature gradient due to the increase of the velocity of flow of the water in the tube. Fig. 8 is interesting in several respects. It illustrates very clearly the effect and importance of the film resistance in all heat transmission problems. It further shows that the film resistance of the metal in the case of tube and plates is much less than the resistance of the films. It may even be used to illustrate why it is possible to lubricate a gas engine with cylinder oil having a flash point of 700° F. while the temperature of the gases in the cylinder may be close to 2500° F.

VI. CONCLUSIONS

The limited nature of these experiments forbids the drawing of any general conclusions other than those already known. The principal interest lies in the development of a method which seems to offer a very desirable means of studying the effect of the variation of the velocity of the flow of gas, steam or water on the rate of flow of heat through tubes, plates, etc.

In order to investigate this subject of the effect of velocity on heat transmission more carefully, means should be provided for maintaining the tube and the water at a constant temperature, while varying the velocity of the latter. In studying the effect on the heat transmission of the velocity of gases over the tube, means should be provided for varying the velocity of the gas, while maintaining a constant temperature of the gas and the tube.

The effect of the formation of steam on the walls of the tube, as it approaches the condition in steam boiler practice, should come in for consideration. It is probable that the effect of rapid agitation of the water in a tube in which steam is forming, especially in large quantities, will be much greater on the heat transmission through the tube to the water, than would be the case in a tube in which no steam was forming, owing of course, to the breaking up and washing off of the steam bubbles from the side of the tube. It might be well to point out here that it is the rate of agitation, and not necessarily the velocity of the water that produces the change in heat transmission. The velocity in feet per second has been used for the reason that it is the only definite quantity available to express this rate of agitation. It may be, to a certain extent, a measure of the rate of agitation, but it is not necessarily so. The rate of agitation may be defined as the number of times per second that each particle of water comes into contact with the tube or with the film on the tube if we consider that the film is indestructible, although it is more likely that the film is in a process of continuous renewal. In the case of the present experiments, it is probable that if elaborate baffles had been placed in the tube, the heat transmission for the same velocity of flow would have been increased. Also, if the stream of water on entering the tube had been given a rotary motion, the heat transmission would have been increased while the velocity through the tube remained constant.

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